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VOL. 40 No. 369 SEPTEMBER 1954

THE INSTITUTE OF PETROLEUM

AN Ordinary General Meeting of the Institute of Petroleum was held at the Institution of Electrical Engineers on 19 March 1954, the Chair being taken by Dr C. B. Davies of the Shell Petroleum Co. Ltd.

The Editor read the minutes of the previous meeting, which were confirmed and signed as a correct record. He then made various announcements.

Dr E. B. Evans, opening the meeting, said: The present symposium on metal-working oils has been arranged on behalf of the Institute and the Publications Committee, by Dr C. B. Davies. Dr Davies has been with the Shell organization since 1941, and has worked on a variety of problems connected with petroleum. Since 1952, he has been manager of the large Central Research organization of Shell at Thornton, and I do not think I need say any more to indicate Dr Davies' knowledge and experience of petroleum in general, and of the particular subjects under discussion. We are very much indebted to Dr Davies for arranging this symposium, and I have much pleasure in asking him to take the chair.

SYMPOSIUM ON METAL-WORKING OILS
PART I. METAL CUTTING

MECHANISM OF FRICTION AND LUBRICATION IN METAL-WORKING*

By F. P. BOWDEN† and D. TABOR†

INTRODUCTION

IN the working and forming of metals it is usual to divide the process into two main parts: the plastic deformation of the metal accompanying the overall change in dimensions, and the frictional effects at the surface of the work as it passes over the die. This sharp division is somewhat misleading as the frictional process itself is not only a surface effect: large tangential forces can produce appreciable shear-deformation of the outermost layers of the work and in deep drawing—particularly in ironing—and in wire drawing the outermost layers may be very heavily worked if the friction is high. It is evident therefore that friction is undesirable not only because of the extra energy that must be expended in overcoming it but also because of the heavy working of the surface layers which in turn involves the danger of fatigue and surface fragmentation.

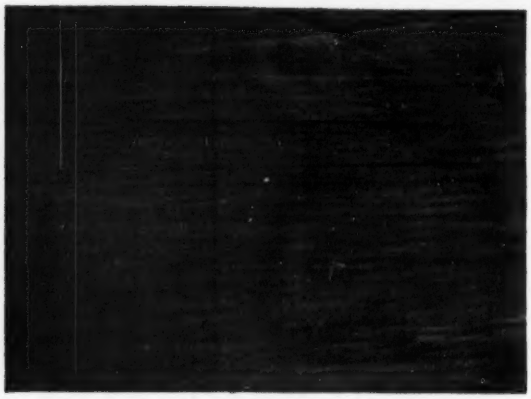
Nevertheless it is probably true to say that in general the greatest disadvantage of friction is the surface damage produced on the work and, in particular, the wear of the die or the forming tool. There are two possible lines of approach in reducing friction and wear. The first is the choice of a suitable die material which, in itself, has good friction and wear properties. The second is the use of appropriate lubricant films. The best practice would clearly involve a combination of both. In this paper both these approaches are dealt with in terms of the basic mechanism of friction and lubrication.

REFLECTION ELECTRON MICROSCOPY

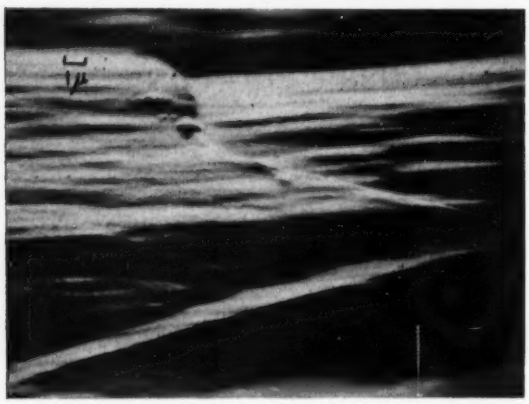
In studying friction and wear it is very important to be able to examine the shape and structure of the surfaces and the surface damage. Several techniques have been used for this purpose including oblique sections, stylus profilometry, multiple beam interferometry, phase contrast microscopy, and transmission electron microscopy involving the use of transparent replicas. Recently Menter [13] has shown that relatively simple modifications can convert the standard Metropolitan Vickers EM3 electron microscope into a reflection instrument. The surface itself is examined directly without the use of a replica. The electron beam is directed at a glancing angle on to the surface and the scattered electrons are focused in the usual way. The resulting electron micrograph reveals the surface contour somewhat in the same way as a pedestrian sees the surface irregularities of a road illuminated by the headlights of an approaching car. Long shadows are cast by the surface irregularities but these are foreshortened because of the small angle of viewing.

A typical reflection micrograph of a mechanically polished copper surface is shown in Fig 1 (*a*), and of an electrolytically polished surface in Fig 1 (*b*). The fine structure of the surface is clearly shown, and it is also seen that there is a large depth of focus. Fig 2 shows the track formed on a highly polished copper surface when a steel hemisphere slides over the surface at a load of less than 1 g. The damage shows the general

* MS received 21 January 1954.
† Research Laboratory on the Physics and Chemistry of Surfaces, Department of Physical Chemistry, Cambridge.



(*a*) REFLECTION ELECTRON MICROGRAPH OF MECHANICALLY POLISHED COPPER SPECIMEN SHOWING THE FINE SURFACE STRUCTURE



(*b*) REFLECTION ELECTRON MICROGRAPH OF ELECTROLYTICALLY POLISHED CADMIUM SHOWING THE TYPICAL "ORANGE-PEEL" SURFACE AND THE CHANGES IN LEVEL AT THE CRYSTAL BOUNDARIES

FIG 1

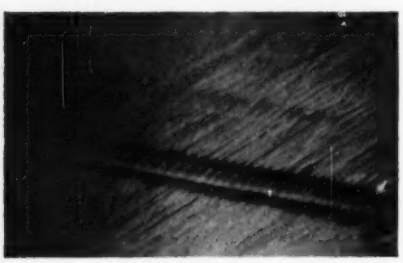


FIG 2

REFLECTION ELECTRON MICROGRAPH OF A FRICTION TRACK FORMED ON MECHANICALLY POLISHED COPPER WHEN A STEEL SLIDER TRAVERSES THE SURFACE AT A LOAD OF LESS THAN 1 G

The grooving and minute chatter marks due to intermittent sliding are clearly seen.

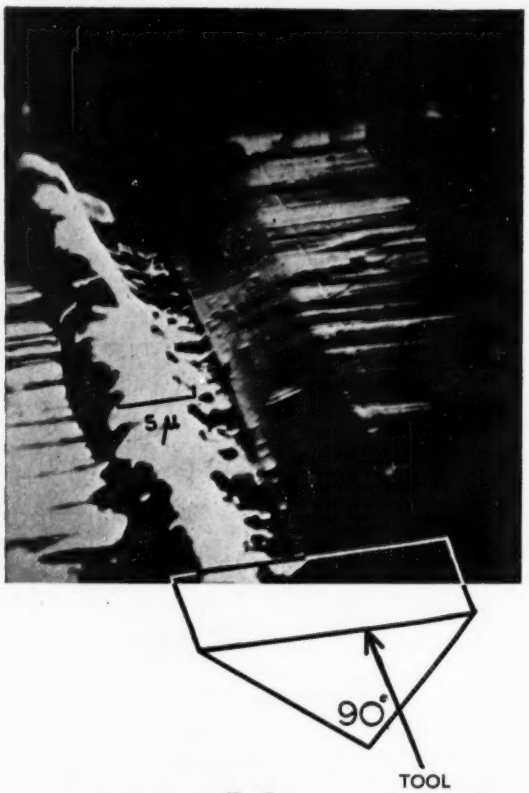


FIG 3

REFLECTION ELECTRON MICROGRAPH OF SURFACE OF ALUMINIUM TURNED WITH A DIAMOND TOOL

The displaced material is thrown up as a parapet on one side of the cut.

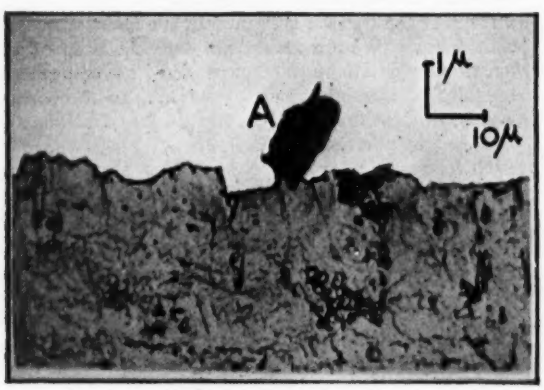


FIG 4

TAPER SECTION SHOWING COPPER FRAGMENT A ADHERING TO A STEEL SURFACE AFTER COPPER HAS SLID ONCE OVER THE STEEL SURFACE

ploughing up of the surface, and on it is superposed a ratchet-like irregularity associated with the intermittent motion which occurred (on a microscopic scale) during sliding. Another interesting example is given in Fig 3. This shows the type of surface damage produced in the machining of an aluminium cylinder with a diamond tool at relatively small loads. The machining operation was carried out by Dr Sayce of the National Physical Laboratory in the formation of a diffraction grating, using the Merton nut. The way in which the material is thrown up as a parapet on one side of the diamond tool is clearly revealed.

It is evident that this technique provides a very useful method for studying problems of surface damage and wear.

THE MECHANISM OF METALLIC FRICTION

It is now generally accepted that the friction between metals arises primarily from strong adhesions at the regions of real contact.[5] Even the smoothest metal surfaces are rough on an atomic scale, and when placed together they initially touch at their high spots only. At these regions the local pressure is sufficient to produce plastic flow, the metals are brought into intimate contact and over these areas cold welding takes place. When sliding occurs these junctions are sheared, and in the course of this shearing process particles may be plucked out of the surfaces. As is to be expected, when a soft metal slides on a harder one, there is relatively heavy plucking of the softer metal (Fig 4). However, by the use of oblique sections and radio-active tracers it may be shown that some transfer of the harder to the softer metal also takes place.

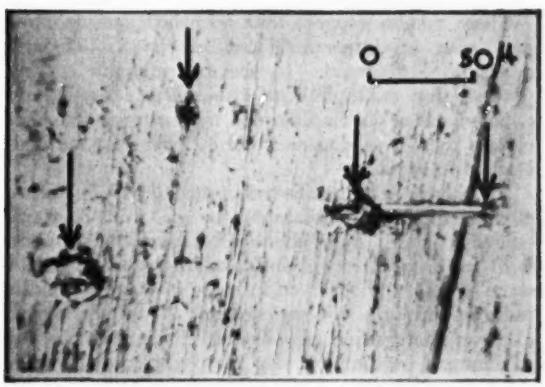


Fig 5

OPTICAL MICROGRAPH SHOWING STEEL FRAGMENTS (MARKED BY ARROWS) ADHERING TO COPPER SURFACE AFTER A FLAT STEEL SURFACE HAS SLID ONCE OVER A FLAT COPPER SURFACE (UNLUBRICATED)

An optical micrograph and an autoradiograph showing this are reproduced in Figs 5 and 6, respectively.[14] The amount is very small and with a good lubricant it will be enormously reduced but with repeated sliding it will gradually lead to wear of the harder metal. The amount of wear may often be reduced by increasing the hardness of the harder metal. This acts in two ways: first, very hard metals are more difficult to pluck on purely physical grounds. Second, the

Fig 6

AUTORADIOGRAPH OBTAINED WHEN A FLAT RADIO-ACTIVE STEEL SURFACE SLIDES OVER A FLAT COPPER SURFACE (UNLUBRICATED)

The black spots correspond to fragments plucked out of the steel and adhering to the copper surface.

harder the metal, the more effectively it will support the surface oxide film.

The importance of the oxide film in friction has been demonstrated in a series of experiments by Bowden and Hughes [3] and by Bowden and Young,[6] who showed that if the oxide film normally present on metal surfaces is removed by heating strongly in a high vacuum it is almost impossible to slide the denuded surfaces over one another: gross seizure occurs even at room temperature, and if the surfaces are finally pulled apart the amount of surface damage is extremely heavy. If a small amount of oxygen (Fig 7) or water vapour (Fig 8) is admitted to the surfaces the friction and surface damage fall to very much lower values. Adhesion occurs at the oxide (or hydroxide) surface, but if the oxide film is not penetrated, shearing occurs within the oxide itself, with a consequent reduction in the friction and wear. If the oxide film is punctured there will be increased metallic interaction, and the friction and plucking will be increased. A more detailed examination by Whitehead [19] and Wilson [20] shows that the penetration of the oxide film is determined primarily by the relative physical properties of the oxide and the substrate. If the substrate is

deformed the oxide must deform with it, if it is to avoid rupture and penetration. If the deformation is sufficiently small practically all oxides will survive relatively intact. Thus, for a given loading, a very hard metal is more likely to maintain the integrity of the oxide film than a soft metal. This effect will be enhanced if the oxide also has suitable properties. It follows that hard metals possessing appropriate oxide films will give reduced friction and wear. This applies to hard chromium and to molybdenum. In some cases a nitrided surface or a carburized surface provides additional support and gives beneficial results. Because of its hardness, tungsten carbide

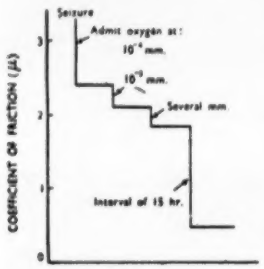


FIG 7

INFLUENCE OF OXYGEN ON THE FRICTION OF CLEAN IRON SURFACES, SHOWING THAT SMALL QUANTITIES OF OXYGEN PREVENT SEIZURE

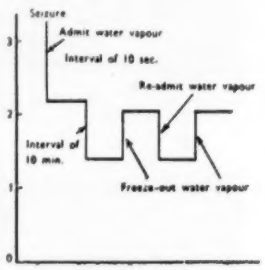


FIG 8

EFFECT OF ADMITTING AND WITHDRAWING WATER VAPOUR ON CLEAN IRON SURFACES

The first major drop in friction is due to a chemically bound film; the later reversible changes are due to van der Waals adsorption.

is also a successful die material, though here it is possible that the cobalt bonding provides a smeared lubricating surface layer (see below).

THE FRICTION AND DEFORMATION OF DIAMOND

Diamond is the hardest material known, its coefficient of friction is low and the adhesion between it and metals is negligibly small. It would therefore seem that diamond would be very well suited for use as a tool or die in the machining or drawing of metals. This is, of course, well established in practice.

Recent experiments [7, 8] have shed some light on the frictional behaviour of diamond under very carefully controlled conditions. If the friction of clean diamond on diamond is measured in air the value is about $\mu = 0{\cdot}1$. If the diamond is heated to a high temperature *in vacuo* to remove films and adsorbed gases, and the friction measured in the vacuum at room temperature, it is found that μ has been increased to about $\mu = 0{\cdot}5$. It is evident that adsorbed surface films are largely reponsible for the low friction of diamond. The effect is shown even more strikingly when a metal slides on diamond (see Table I). Under clean atmospheric conditions $\mu = 0{\cdot}2$. When surface films are removed from both surfaces in a vacuum the friction may reach as high a value as $\mu = 3$, and particles of the metal may be plucked out of the metal surface and left adhering to the diamond. (It is interesting to note that with graphite a similar plucking of the metal may occur when the surfaces are clean.)

Again, if direct adhesion measurements are made it is found that there is negligible adhesion of diamond to

TABLE I
Friction of Diamond

Surfaces	Condition	Coefficient of friction μ
Diamond on diamond	In air	0·05 to 0·1
Diamond on diamond	After cleaning *in vacuo*	0·5
Metal on diamond	In air	0·2
Metal on diamond	After cleaning *in vacuo*	3

hard metals in air but appreciable adhesion when the surfaces are thoroughly cleaned *in vacuo*. Some typical results by Dr Rowe are given in Table II, the coefficient of adhesion being defined as the force required to pull the surfaces apart divided by the original joining load.

TABLE II
Adhesion of Diamond to Metals

Surfaces	Condition	Coefficient of adhesion
Diamond on Platinum	In air	0
Diamond on Platinum	After cleaning *in vacuo*	0·4

These results suggest that adsorbed surface films may play an important part in the friction and adhesion of diamond. In the drawing and cutting process, for example, the rubbing of the freshly exposed metal on the diamond may correspond more closely to the conditions described here for surfaces cleaned *in vacuo*.

Another interesting observation concerns the nature of the deformation of diamond surfaces when they rub on one another. It is generally assumed that diamond is so hard that the local deformation is elastic, and to some extent, the observed increase of μ as the load is reduced supports this assumption. However, recent electron micrographs suggest that during the rubbing of diamond on diamond slip has occurred along well-defined slip-planes. Thus examination of a diamond surface which has been abraded with diamond dust in one direction shows that the abrasion grooves are traversed by a series of fainter lines running at an angle to them. These fainter lines correspond to the intersection of the octahedral planes with the surface.[17] This suggests that plastic deformation of the diamond has occurred. It is also found that the friction of diamond on diamond varies with the crystallographic face and direction, and may be very much higher along the softer direction ($\mu = 0{\cdot}15$) than along the harder

($\mu \simeq 0{\cdot}05$). It is possible that this is associated with increased ploughing or " digging in " along the softer direction.

These observations show that in spite of the excellent frictional and wear properties of diamond there are many complicating factors that may have an important bearing on its practical performance as a die or tool material.

MECHANISM OF BOUNDARY LUBRICATION

The main purpose of a lubricant is to provide a film which separates the sliding surfaces and is, in itself, easily sheared. Lubrication is most effective when the lubricant builds up a hydrodynamic film sufficiently thick to prevent even the asperities of the surfaces from coming in contact. The wear is negligible and the friction extremely low. Unfortunately the pressures involved in most metal-forming operations are too high for hydrodynamic lubrication of this type to be attained with conventional lubricants. The lubricant is squeezed out until a film of only a few molecular layers is left between the work and the die. The protective properties of " boundary " films of this type depend on the physical and chemical nature of the film as well as on the properties of the substrate.

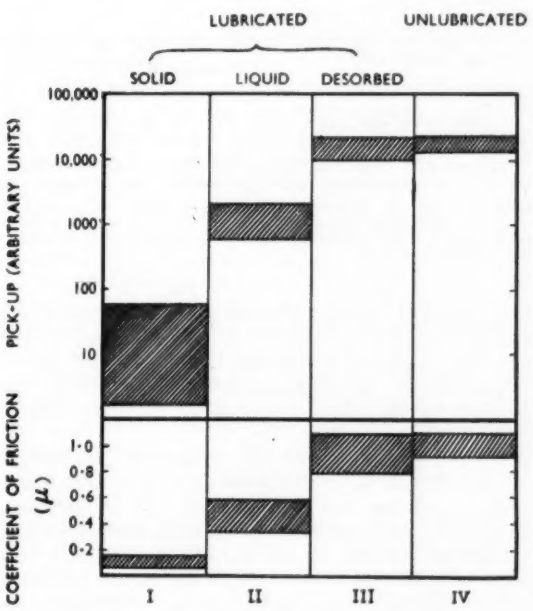


FIG 9

DIAGRAM SHOWING FRICTION AND METALLIC TRANSFER FOR LUBRICATED SURFACES WHEN THE LUBRICANT FILM IS : (I) SOLID, (II) LIQUID, AND (III) DESORBED

The behaviour when the film is desorbed is almost the same as for unlubricated surfaces (IV).

The most important factor determining the protective properties of the boundary film is its physical state. The best protection is provided when the film is solid; at the melting point there is a marked increase in friction and damage, and at a somewhat higher temperature a further deterioration occurs. These changes are shown clearly by sliding a radio-active slider over a non-radio-active surface and observing by an autoradiographic technique the amount of radio-active transfer.[15] The results show that when the boundary film is solid the amount of metallic interaction may be reduced by an enormous factor. Thus whilst the friction between unlubricated metal surfaces in air has a value of about $\mu = 1$, and this may be reduced by a good boundary lubricant by a factor of about 20 ($\mu = 0{\cdot}5$), the metallic transfer may be reduced by a factor of 20,000 or more (Fig 9, Column 1). If the temperature is raised until the lubricant film melts, the film loses its rigidity, and a large increase in metallic interaction occurs. The friction rises by a factor of 5 to 10, while the metallic transfer may increase a thousandfold (Fig 9, Column 2).

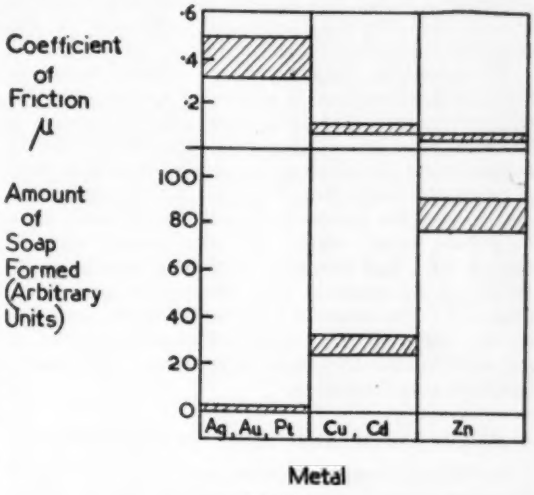


FIG 10

DIAGRAM SHOWING HOW BOUNDARY LUBRICATION BY FATTY ACIDS DEPENDS ON CHEMICAL REACTION

On inert metals (silver, gold, platinum) lubrication is poor. When heavy soap formation occurs (cadmium, zinc) lubrication is very effective.

The lubricant film, though liquid, still provides some protection, since the molecules are still attached to the solid surface. At higher temperatures further deterioration takes place. The friction increases by a small factor, but a further large increase in metallic interaction and metallic transfer occurs. At this stage the friction and surface damage are characteristic of unlubricated metal, although lubricant is visibly present on the surface (Fig 9, Columns 3 and 4). The lubricant film is now desorbed or completely mobile. These changes are reversible on cooling since, as mentioned above, these correspond to changes in state of the lubricant film. With prolonged heating, oxidation of the lubricant occurs, and the behaviour is then determined by the properties of the oxidation products.

The effectiveness of lubricant films in the solid state explains the superiority of fatty acids over paraffins and alcohols. In general, the fatty acids react with the surface to form metallic soaps, and these have an appreciably higher melting point than the parent fatty acids. This reaction is greatly facilitated by the presence of moisture on the surface.

The overriding importance of chemical attack in fatty acid lubrication is shown by a very sensitive radio-active method [4] for detecting the occurrence of chemical reaction. The results show that if no reaction occurs the lubrication provided by a fatty acid is relatively ineffective (Fig 10). This investigation also yielded the interesting result that in some cases long-chain esters could react with metals, such as copper, zinc, and cadmium, to form a metallic soap, and when this occurred very effective lubrication was obtained. The reaction may be due to the presence of fatty acid impurity; if there is moisture present at the metal surface hydrolysis of the ester would clearly facilitate soap formation.

FATTY ACID AND SOAP LUBRICATION

In ordinary running mechanisms it is very important that the boundary film should be able to reform itself if it is worn away by the sliding process. For this reason dilute solutions of fatty acids are generally more effective than suspensions of soaps. Further, the metallic soap formed by chemical attack at the metal surface is often several molecules thick, and so provides better protection than the monomolecular soap film physically adsorbed from a soap solution or emulsion. In metal-working operations, however, the work passes over the die only once and the problem of film repair is relatively unimportant. For this reason, the use of a soap film as distinct from a fatty acid solution offers the great advantage that a metal soap of relatively high melting point may be chosen and applied as a thick film to the work before it is subjected to the forming process. If, however, the soap film contains an appreciable amount of water, ebullition of the water may occur if the temperatures exceed 100° C, and the film will lose its protective properties well below the melting point of the film. The soap film will therefore be more effective if it is applied dry, either by deposition from a hot aqueous emulsion or from a solution in a volatile solvent.

SULPHUR AND CHLORINE LUBRICANTS

Most long-chain lubricants, such as metallic soaps, are melted or desorbed above 200° C. For effective lubrication above this temperature surface films possessing a higher melting point must be used. This forms the basis of lubricant additives containing labile sulphur or chlorine or both.[11, 12] These additives function by reacting with the surface to form, in general, the metal sulphide or chloride *in situ*, and these films provide protection of the underlying material up to their melting points or decomposition temperatures. Because the sulphides usually have higher melting points and are chemically more stable they are effective up to higher temperatures than the corresponding chloride films. Thus on ferrous materials [16] the sulphide is effective up to 800° C, the chloride up to 400° C only (Fig 11). On the other hand, the sulphide films are not easily sheared and the friction is relatively high. In contrast, many chlorides have a layer structure and the friction may be appreciably lower. It follows that if the temperature between the work and the die is not too high, chloride additives are generally better; but if very

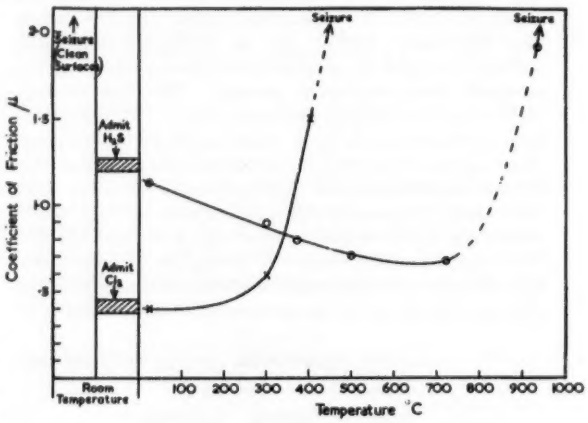


FIG 11

EFFECT OF H_2S AND Cl_2 ON THE FRICTION OF IRON SURFACES THOROUGHLY CLEANED IN A VACUUM

The sulphide film, formed by the H_2S, prevents seizure, the friction lies between $\mu = 1$ to 0·6 and the protection is effective up to temperatures greater than 800° C. The chloride film, formed by the Cl_2, produces a much greater reduction in friction but it ceases to be effective above about 400° C.

high temperatures are reached sulphur additives are preferable. Since, in order to avoid corrosion, the additives must not be too reactive, it is often advantageous to add small quantities of fatty acid to the additive so that effective lubrication may be provided at lower temperatures.

In cutting, drilling, and similar machining operations one of the main functions of the lubricant is to act as a coolant and here the thermal properties of the lubricant are of great importance. As far as the lubricating properties themselves are concerned there are two additional factors in these types of operations which do not arise in drawing or extrusion. The first is the accessibility of the lubricant to the work. The way in which a lubricant actually reaches the freshly bared metal chip as it flows over the leading edge of the tool is still a contentious issue. A clearer and less equivocal answer to this might lead to the development of more effective machining fluids (see below). The second factor is the rate of reaction of the lubricant with the work to form a good protective film. In high-speed operations the chip is formed and has

passed beyond the cutting tip of the tool in perhaps less than 10^{-4} sec. The lubricant must have formed a lubricating film in less than this time if it is to be effective. Fortunately, rapid reaction is favoured by the fact that the chip is naked metal and that the surface temperatures are very high. Further, a more corrosive lubricant is permissible in machining operations than in continuously running mechanisms, such as gears, where the same surface is being repeatedly traversed. In spite of these factors the speed of reaction may be crucial, and in some cases a very reactive additive may for this reason prove more effective, even though its intrinsic lubricating properties under more leisurely conditions may be inferior to those of a less reactive material. A preliminary account of a simple direct investigation of the effect of sulphide films on the cutting of metals is given in the last section of this paper.

METALLIC FILM LUBRICATION

Another method of reducing friction and wear is to coat the metal surface with a thin film of a softer metal. If the film is appreciably thicker than the surface irregularities and the deformation or stretching of the underlying metal is not too great the substrate may be completely protected and the whole of the shearing will occur within the softer surface film itself. The softer the film, the lower the friction, but there is clearly a limit to this, for if the film is too soft it may be squeezed out during sliding and the underlying surfaces may come into direct contact. Further, the films become relatively ineffective above their melting points, and soft materials usually have low melting points. Thus indium films, which may give coefficients of friction of less than $\mu = 0{\cdot}04$, melt at 155° C and are not particularly effective above this temperature. Other materials which are suitable are lead (m.p. 327° C), zinc (m.p. 420° C), and copper or silver (m.p. >900° C) (see Fig 12). Films of copper or silver will clearly be useful only in the working of very much harder metals, such as steel.

Phosphide coatings may function, to some extent, in the same way, though their detailed action is by no means clear and merits further study. For example, it is well known that they are really effective only when they are themselves lubricated with a conventional lubricant.

Soft metallic films are, of course, worn away during sliding and, in metal working it is therefore desirable to apply the coating to the work rather than to the die or tool. Nevertheless, there are possible ways of using metallic film lubrication in the die; this may be done by dispersing the soft component in a harder porous matrix. During sliding the softer metal is expressed and smeared over the surface to replenish the protective film. As is well known, this forms the basis of copper–lead-bearing alloys, but the extension of this idea to dies and tools has not been systematically followed up. Some work on sintered tungsten carbide tools suggests that the cobalt bonding is smeared over the surface and acts as a lubricant film in this way,[18] but further work on this is desirable.

It is interesting to compare metallic film lubrication with that provided by conventional long-chain organic materials, such as oils, greases, and soaps. Both function by providing a thin surface film which separates the surface and which, in itself, is easily sheared. Both are most effective where they are in the solid state. Both when operating under optimum conditions can reduce the amount of metallic interaction to such a low level that the wear is negligibly small. Under these conditions practically the whole of the resistance to sliding is due to the force required to shear the lubricating film itself. It is here that a very

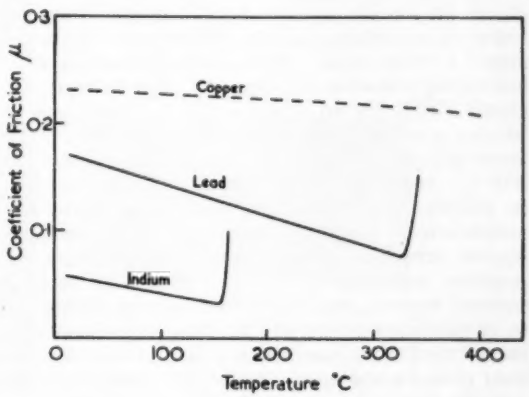


FIG 12

FRICTION OF STEEL SURFACES LUBRICATED WITH THIN FILMS OF INDIUM, LEAD, AND COPPER (10^{-4} TO 10^{-5} CM THICK)

With increasing temperature the film softens and the friction falls, but at the melting point the film loses its protective properties and the friction rises. (It should be noted that the actual value of the coefficient of friction depends on the film thickness, the geometry of the slider, and on the load, so that the absolute values of μ for the different films are not strictly comparable.)

marked difference is observed in the properties of metal films and conventional lubricants. With metals the shear properties are practically independent of hydrostatic pressure. The film trapped between the sliding surfaces may be subjected to hydrostatic pressures comparable to the yield pressure of the metal substrate (say 10,000 atmospheres). Nevertheless, the shear strength of the lubricating metal film will be almost the same as that observed under atmospheric conditions. The position is very different for long-chain compounds. The strength properties increase enormously as the pressure on them is increased.[9] Liquids become extremely viscous or even plastic solids. Soft waxy materials become extremely hard and strong. Although this leads to an increase in the force required to shear the lubricant film, *i.e.* the friction is increased, it also means that the oil film is very much tougher than under atmospheric conditions and very much more resistant to penetration and rupture. This property must play a

very important part in determining the efficacy of a conventional lubricant. In particular, it probably explains why some measure of hydrodynamic lubrication is obtained under conditions where it seems impossible. Recently, Christopherson [10] has shown that if very high pressures are built up in a liquid lubricant a hydrodynamic film can be formed even in the wire drawing process; this will clearly be considerably facilitated by the effect of high pressures on the viscosity of the oil. This aspect of lubrication merits a great deal of further attention.

NEW MATERIALS

It has been pointed out that in theory at least, it should be possible to fabricate a self-lubricating die material, consisting of a hard matrix in which is dispersed a softer metal. Instead of a soft metal other lubricating materials may be used. For example, the plastic PTFE has an exceptionally low coefficient of friction ($\mu \approx 0{\cdot}05$), and if impregnated into the surface layers of a porous metal gives a very low friction up to 300° C. Other materials which may be incorporated to provide low friction surfaces are graphite and molybdenum disulphide, both of which possess a layered structure. For example, molybdenum disulphide, impregnated in a porous backing such as sintered copper, gives a low coefficient of friction up to elevated temperatures. In these experiments [1] a curved steel slider was used at a load of 4 kg, but the local pressure was equal to the yield pressure of the sintered copper, *i.e.* about 40 kg/mm² or 60,000 p.s.i. The results are given in Table III.

TABLE III

Friction of Steel Sliders on Copper Surfaces

Surface	Coefficient of Friction				
	Temperature ° C				
	15	100	200	300	400
Solid copper	1·3	1·3	*c*1·0	*c*1·0	*c*1·0
Sintered copper	0·3	0·7	0·8	1·2	1·2
Sintered copper containing molybdenum disulphide	0·13	0·14	0·13	0·14	0·2

The results are striking, and it is interesting to note that a material such as this has found practical application as a low-speed bearing operating at nominal pressures of the order of 30,000 p.s.i.

A further extension of this is to use sintered molybdenum as the tool material and to attack it chemically to form the disulphide *in situ*. Under these conditions the disulphide is firmly attached and penetrates to some depth below the surface. Recent experiments have shown that such surfaces have a low coefficient of friction, and even when running hot the coefficient of friction may be less than $\mu = 0{\cdot}1$. The molybdenum disulphide film may be worn away, but it is replenished from the pores during repeated sliding. This type of approach may lead to the development of new die and tool materials in the working and machining of metals.

THE EFFECT OF GASES ON THE CUTTING OF METALS

It has been shown that the friction of metal is very dependent on the nature of the gas which surrounds it. Some study of the influence of gaseous atmosphere on the cutting of metals is being made by Bowden and Priddle (unpublished). As mentioned above, it is usually considered that a cutting fluid has two main functions. First, to act as a " coolant "; that is to carry away the heat generated at and near the tip of the tool. This heat is developed partly by plastic deformation of the metal and partly by friction on the tool. For cooling purposes liquids of high thermal conductivity, high heat capacity, and high latent heat of evaporation should be the most effective. The second function is to reduce the adhesion and friction between the surface of the tool tip and the metal turning.

By using different gases we may, to some degree, separate these functions. All gases will, in comparison with liquids, be ineffective as " coolants," but if suitably selected they may have a marked effect in reducing the friction. Some experiments have been made on the cutting of aluminium with tools of steel and of molybdenum in air and in an atmosphere of gaseous hydrogen sulphide. The cutting speed was *c.* 370 f.p.m. and depth of cut 0·01 inch. All the surfaces were carefully degreased, so that any lubricating effect is due to the gas.

RESULTS WITH A STEEL TOOL

The tool was V.A.P. steel with a hardness of 950 V.P.H. The hardness of the pure aluminium was *c.* 30 V.P.H. The results obtained in air with no cutting fluid are reproduced in Fig 13 (*a*) and (*b*), which shows a photomicrograph of the tool tip after cutting and of the aluminium surface together with a trace which records the surface finish. It will be seen that there is marked pick-up of the aluminium on the tip of the tool and the average surface roughness is 28 microinches. Fig 13 (*c*) and (*d*) shows the results obtained in an atmosphere of hydrogen sulphide. The aluminium pick-up on the tool is now very small, the finish improved, and the average surface roughness reduced to 18 microinches. Fig 13 (*e*) and (*f*) shows the results obtained when a good commercial cutting oil recommended for aluminium is used. There is little pick-up on the tool, and the average surface roughness is 19 microinches.

These results are striking. They show that, under the conditions of this experiment an atmosphere of H_2S can reduce the pick-up on the tool, and can produce a surface roughness which is comparable to that obtained with a good cutting fluid.

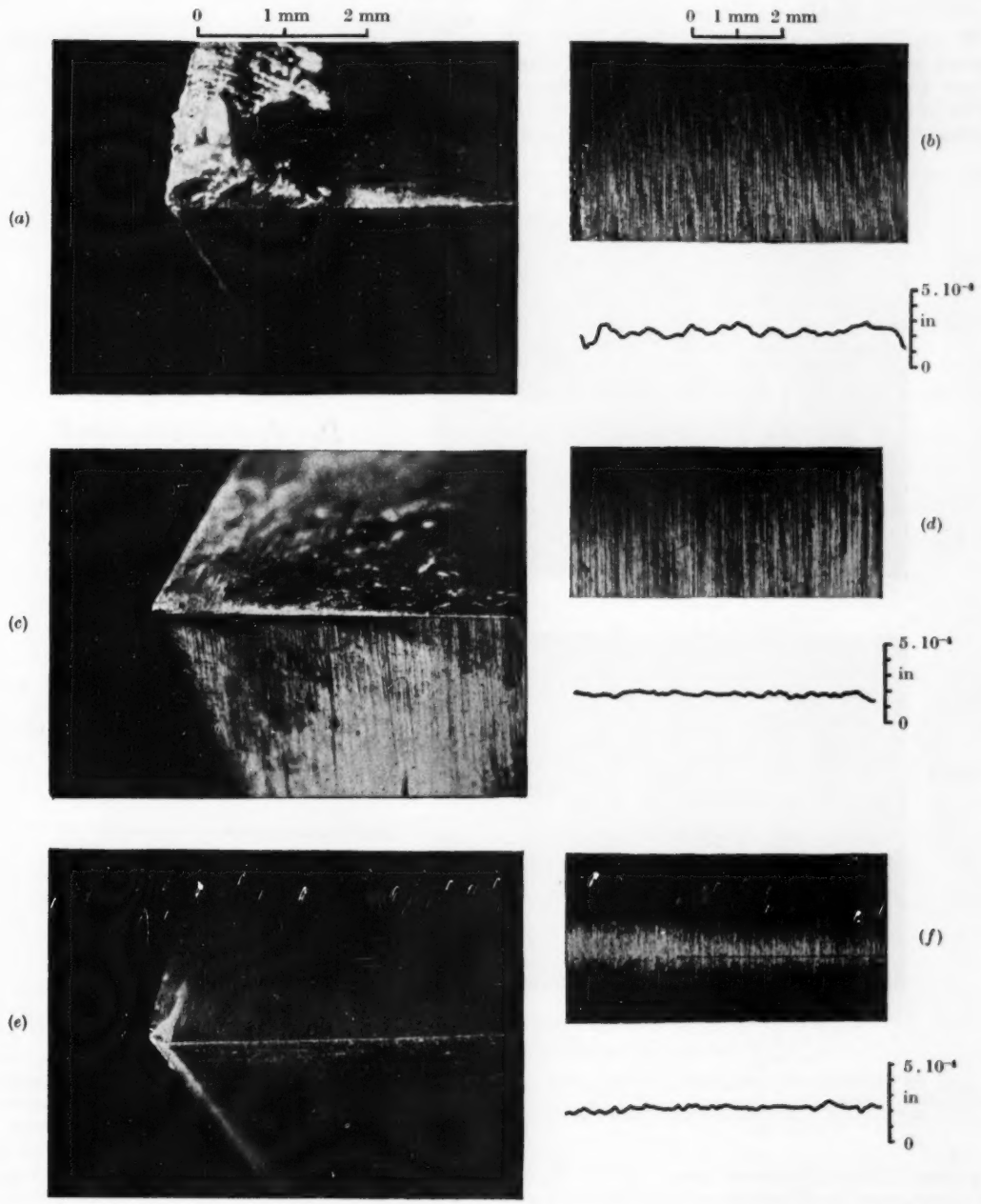


FIG 13

CUTTING OF ALUMINIUM SURFACE WITH STEEL TOOL

(*a*, *b*) No lubricant: (*a*) tool showing heavy pick-up of aluminium; (*b*) surface showing rough finish and profilometer record.
(*c*, *d*) H_2S gas: (*c*) tool showing slight pick-up; (*d*) surface showing finer surface finish.
(*e*, *f*) Commercial sulphurized lubricant. The small pick-up on the tool and the surface roughness are similar to those obtained with H_2S gas.

RESULTS WITH A MOLYBDENUM TOOL

It has been shown that molybdenum disulphide formed *in situ* by the attack of H_2S on the hot metal [2] forms an excellent lubricant film. An analogous series of experiments was therefore carried out with tools of molybdenum cutting in air and in H_2S. The reduced to 45 microinches. This is a very large reduction.

These observations give interesting information on the mechanism of the action of a cutting fluid because they bring out two points clearly. The first is that apart altogether from any cooling action the reduction of the friction between the tool and the metal can be

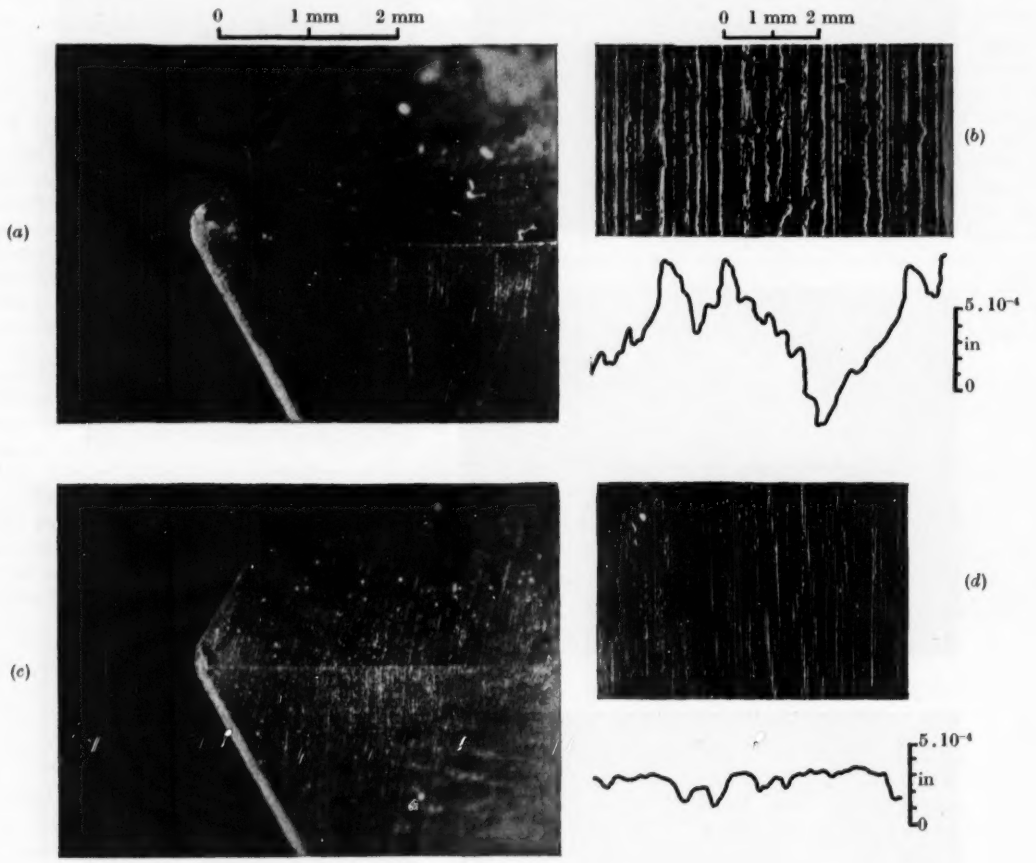


FIG 14

CUTTING OF ALUMINIUM SURFACE WITH MOLYBDENUM TOOL

(*a*, *b*) No lubricant: (*a*) tool showing heavy pick-up of aluminium; (*b*) surface showing very rough surface finish and profilometer record.
(*c*, *d*) H_2S gas: (*c*) tool showing minute pick-up; (*d*) surface showing very much finer surface finish.

hardness of the molybdenum, about 230 V.P.H., was, of course, very much less than that of the tool steel. Fig 14 (*a*) and (*b*) shows the results obtained with unlubricated molybdenum cutting aluminium in air. There is pick-up on the point of the tool, and the surface finish is very poor. The average roughness is 190 microinches. When an atmosphere of H_2S is used there is a very marked improvement (see Fig 14 (*c*) and (*d*)). The pick-up on the tool is small, the surface finish reasonably good, and the average roughness of the first importance. The second is that an appropriate gaseous atmosphere can itself act as a " cutting fluid " and give an improved cutting and surface finish. Under the conditions used in many practical operations it is difficult to see how the cutting liquid as such could reach the point of rubbing contact between the tool and the metal because of the high speeds and close contact between the surfaces. A gas or vapour could, however, penetrate much more readily. The experiments indicated that under these

conditions a function of the cutting fluid may be to surround the tip with an atmosphere of an appropriate gas which is capable of attacking very rapidly the freshly exposed metal surface to form a lubricating film.

ACKNOWLEDGMENT

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A PRELIMINARY INVESTIGATION OF THE EFFECTIVENESS OF VARIOUS CHLORINATED HYDROCARBON COMPOUNDS AS CUTTING OIL ADDITIVES*

By K. J. B. WOLFE,† M. D. KINMAN,† and G. LENNARD†

THREE groups of chlorinated hydrocarbons—substituted methanes, ethanes, and ethylenes—were tested as additives to a straight hydrocarbon mineral oil. Testing was done by using the oil plus additive as a cutting lubricant for drilling under controlled conditions. Specific and markedly significant results were obtained between the three groups and from individual compounds within each group.

Considerable exploratory test work has been done to develop a technique which would eliminate outside factors which could affect the significance of the results, and particulars of this work and details of the test are given in the Appendix. Results of the final tests are as shown in Tables I, II, III, and IV.

With the substituted ethanes and methanes it was found that an increase in the number of chlorine atoms in the molecule is followed by an increase in its effectiveness as an additive; with the substituted ethylenes a decrease in effectiveness was found with an increasing number of chlorine atoms in the molecule.

There are indications that the maximum effectiveness is obtained with a relatively low concentration of additive, and the optimum degree of concentration varies with the compound used.

Previously Planteneva and Epifanov found, under different conditions, that effectiveness was increased with increasing concentration. It was also found that several compounds of the ethane group were more effective than carbon tetrachloride, which had been found by Shaw, Planteneva, and Epifanov to reduce the coefficient of friction between the chip and the tool face to a lower value than with other compounds. Planteneva and Epifanov also found that the use of

TABLE I

Drill Test Results Using Additives from Substituted Ethane Group

Additive	Number of chlorine atoms per molecule	Amount of additive per 1000 cc oil	Viscosity at 27° C No. 1 Redwood	Average number of holes drilled per drill
Di-chlor-ethane CH_2Cl–CH_2Cl	2	15·8 cc; 14·3 g chlorine	325	416
β-trichlorethane, CH_3CCl_3	3	12·5 cc; 14·3 g chlorine	312	1157
Tetrachlorethane, $CHCl_2$–$CHCl_2$	4	10·6 cc; 14·3 g chlorine	315	1298
Pentachlorethane, $CHCl_2$–CCl_3	5	9·7 cc; 14·3 g chlorine	333	1351
Hexachlorethane, CCl_3–CCl_3	6	15·8 g; 14·3 g chlorine	367	1494

* MS received 29 January 1954.

† B.S.A. Group Research Machinability Laboratories.

carbon tetrachloride causes increased wear of the cutting tool. This is indicative that the measurement of the coefficient of friction between chip and tool face may not be a reliable indication of a compound's value as a cutting lubricant additive.

It would appear that the effectiveness of an additive depends on a number of factors, such as concentration, type of material being machined, nature of machining operation, temperatures evolved at seat of cutting, and speeds and feed of the cutting tool. In view of these variable factors, the results of any test, except those which exactly simulate working conditions, must be accepted with caution and used with discretion.

It will be appreciated that the compounds used in this investigation are toxic, and the main purpose in using them was to try and establish a relationship between the molecular structure of the compounds used and the effectiveness as a cutting oil additive, but in view of the low concentrations which have been found effective, it may be possible to use these compounds under particular conditions.

TABLE II

Drill Test Results Using Additives from Substituted Methane Group

Additive	Number of chlorine atoms per molecule	Amount of additive per 1000 cc oil	Viscosity at 27° C No. 1 Redwood	Average number of holes drilled per drill
Methylene chloride, CH_2Cl_2	2	12·8 cc; 14·3 g chlorine	276	137
Chloroform, $CHCl_3$	3	10·8 cc; 14·3 g chlorine	320	847
Carbon tetrachloride, CCl_4	4	9·7 cc; 14·3 g chlorine	330	1111

TABLE III

Drill Test Results Using Additives from Substituted Ethylene Group

Additive	Number of chlorine atoms per molecule	Amount of additive per 1000 cc oil	Viscosity at 27° C No. 1 Redwood	Average number of holes drilled per drill
Dichlorethylene, CHCl=CHCl	2	15·4 cc; 14·3 g chlorine	284	648
Trichlorethylene, $CHCl–CCl_2$	3	12 cc; 14·3 g chlorine	300	153
Perchlorethylene, $CCl_2–CCl_2$	4	10·3 cc; 14·3 g chlorine	337	109
Straight oil, no additive	—	—	370	42

TABLE IV

Order of Effectiveness Chlorinated Hydrocarbon Additives 14·3 Grammes Chlorine to 1000 cc Straight Mineral Oil Used at 27° to 30° C

Additive	Number of chlorine atoms per molecule	Volume of additive per 1000 cc oil	Average number of holes drilled per drill
Hexachlorethane	6	15·8 g (solid)	1494
Pentachlorethane	5	9·7 cc	1351
Tetrachlorethane	4	10·6 cc	1298
β-trichlorethane	3	13·5 cc	1157
Carbon tetrachloride	4	9·7 cc	1111
Chloroform	3	10·8 cc	847
Dichlorethylene	2	15·4 cc	648
Di-chlor-ethane	2	15·8 cc	416
Trichlorethylene	3	12 cc	153
Methylene chloride	2	12·8 cc	137
Perchlorethylene	4	10·3 cc	109

APPENDIX I

The data given in the foregoing paper have been obtained by a series of drilling tests, based on a method developed by the B.S.A. Group Machinability Laboratory for the testing of cutting oils.

This consists of a series of comparative tests using drills and test blocks of known quality, and the number of holes drilled before drill failure, based on an

TABLE V

Drill Test Results Using a Straight Hydrocarbon Cutting Oil Cutting Lubricant plus Additive

Test number	Number of holes drilled	Average number of holes drilled	Additive and percentage added by volume	Remarks
1	24 28 22	25	Straight oil, no additive	
2	270 281 521 603	Results too scattered; test invalid	Di-chlor-ethane, 2%	
3	48 78 122	"	Di-chlor-ethane, ½%	
4	416 427 406	416	Di-chlor-ethane, 1%	Oil heated to 27° C prior to start of test.
5	704 742 694	713	Di-chlor-ethane, 2%	Oil heated to 27° C prior to start of test.
6	1118 1102	1110	Di-chlor-ethane, 4%	Oil heated to 27° C prior to start of test.
7	527 473	500	Di-chlor-ethane, 8%	Oil heated to 27° C prior to start of test.
8	817	817	Di-chlor-ethane, 6%	Oil heated to 27° C prior to start of test.
9	40 47 38	42	Straight oil, no additive	Oil heated to 27° C prior to start of test.

average of three drills, is taken as a measure of the effectiveness of the cutting lubricant.

The drills and test blocks are first tested, using a soluble oil of known quality as a check on the machining qualities of the test block and to eliminate any drills which may be metallurgically faulty. The drills are then resharpened and used on the test proper.

Scattered results are an indication that unknown factors are present or that conditions are not in equilibrium. The test is therefore continued and, if necessary, conditions are modified until repeatable and consistent results are obtained. The repeatability of the results can be taken as a measure of the validity of the tests.

APPENDIX II

The following is a record of the conditions of test and of the work done in stabilizing conditions until repeatable results were obtained.

A Corona sensitive drilling machine is employed; the feed being hand-controlled by the operator working in time with a clock graduated in $\frac{1}{5}$ seconds. Hand feed is preferable to power feed for the size of drill used ($\frac{1}{8}$ inch diameter), and an experienced operator can maintain a remarkably uniform rate of penetration.

TABLE VI

Drill Test Results Using a Straight Hydrocarbon Oil Plus Additive as a Cutting Lubricant

Test number	Number of holes drilled	Average number of holes drilled	Additive 1% chlorine by volume	Remarks
10	51 44 57	51	Methylene chloride	
11	74 518 529 589	545	Chloroform	First result discarded — performance rising
12	664 759 783	738	Carbon tetrachloride	Performance rising.
13	707 691 754	717	Tetrachlorethane	
14	137 608 655 684	649	β-Trichlorethane	First result discarded — performance rising.
15	66 69 88	74	Trichlorethylene	Performance rising.
16	812 801 850	821	Pentachlorethane	
17	124 113 127	121	Perchlorethane	
18	600 571 607	593	Dichlorethylene	

Oil heated to 27° C prior to start of tests.

TABLE VII

Drill Test Results Using a Straight Hydrocarbon Oil Plus Additive as a Cutting Lubricant

Test number	Number of holes drilled	Average number of holes drilled	Additive 14·3 g chlorine per 1000 cc oil	Remarks
19	1118 1088 1126	1111	Carbon tetrachloride	
20	1365 1338	1351	Pentachlorethane	
21	1270 1326	1298	Tetrachlorethane	
22	100 90 137	109	Perchlorethylene	
23	669 632 643	648	Dichlorethylene	
24	818 923 801	847	Chloroform	
25	730 1171 1114 1185	1157	β-trichlorethane	First result disregarded.
26	143 141 128	137	Methylene chloride	
27	190 133 135	153	Trichlorethylene	
28	1516 1472	1494	Hexachlorethane	

Conditions of Test

Drills $\frac{1}{8}$ inch diameter, jobbers' length.
Depth of hole drilled, $\frac{3}{4}$ inch.
Spindle speed, 3340 r.p.m.
Cutting speed, 109 f.p.m.
Time to drill one hole, 3 seconds.
Rate of penetration, 15 inches per minute.

Di-chlor-ethane was chosen for the preliminary tests, as it appeared to be one of the least toxic, and the amount used gave roughly 2 per cent chlorine addition by volume when added to the carrier, which was a straight hydrocarbon oil. This oil was previously tested without any additive.

APPENDIX III

Very scattered results were obtained at first and on investigation it was found that the scatter was due to variation in the oil temperature, rising from that in the room (21° C) to a fairly stable level of 27° to 29° C during the course of the test. On preheating the oil

to 27° C before the test commenced, consistent and repeatable results were obtained.

Tests were then made to find the result of increasing the concentration of the additive, and it was found that the optimum was in the region of 4 per cent by volume. The performance had then reached such a high level, 1110 holes per drill, that it was decided to carry out the comparative tests using a 1 per cent concentration of additive to reduce the amount of work involved.

Having established suitable conditions, the range of compounds under investigation was tested, using the same volume of additive in each case. The results are given in Tables V and VI.

The results obtained showed, in some instances, a slight scatter, the values obtained rising during the course of the test. This indicates that equilibrium of conditions had not been achieved, and some of the results were somewhat unexpected, so the tests were repeated. This time the chlorine additive was added on a weight basis, and the temperature of the oil was more closely controlled. The detailed results of these tests (see Table VII) were very orderly, and form the basis of this paper.

SOME ASPECTS OF THE METAL CUTTING PROCESS*

By GEO. V. STABLER†

INTRODUCTION

THE value of cutting fluids in metal machining was first assessed by trial and error in the workshop. This has been followed by a great deal of scientific research into the application of the fluids, a matter which has been assisted by the discovery of new information about what happens in cutting. The object of this paper is to present in a condensed and descriptive form some of the known facts of the cutting process in order to state the problem. It is difficult to epitomize so vast and complex a subject, but even more difficult to solve the problems associated with fluids.

SHEAR ACTION

The predominant cutting action is that of a high degree of plastic shear usually occurring at a high rate. As the metal approaches the tool it is subject to an increasing compressive stress. Within the elastic limit the resulting strain and change of direction are very small. After the elastic limit the strain is very great and large changes of direction occur. The variation in the rate and degree of strain cause the different types of chip experienced in practice, the differences being caused much more by the physical and metallurgical characteristics of the metal being cut than by the material of the tool.

If the shear occurs uniformly over a flat plane extending between the cutting edge and the outer surface of the approaching work the action is continuous and without fracture, so that a continuous straight chip flows over the rake face of the tool. This condition is presumed in Merchant's shear theory, the angle between the shear plane and the work surface being called ϕ. It is most nearly approached when cutting ductile materials under good conditions at high speed, and it results in a good surface finish. A section of such cutting is shown in Fig 1.

Study of microphotographs of cutting show that the shear plane, ideally of zero thickness, commonly has a thickness between 0·001 and 0·010 inch, although the latter figure may be greatly exceeded. Most cutting speeds are between 50 and 500 f.p.m., although these limits are greatly exceeded in both directions, *e.g.* by screwcutting and by grinding. Taking the narrower limits, we may calculate that the metal passes through the shear plane in something between 10^{-3} and 10^{-5} seconds. It should be noted that the shear occurs in the interior of the metal, and that only "lubricants," such as lead, sulphides, and graphite, in the interior of the metal can affect it.

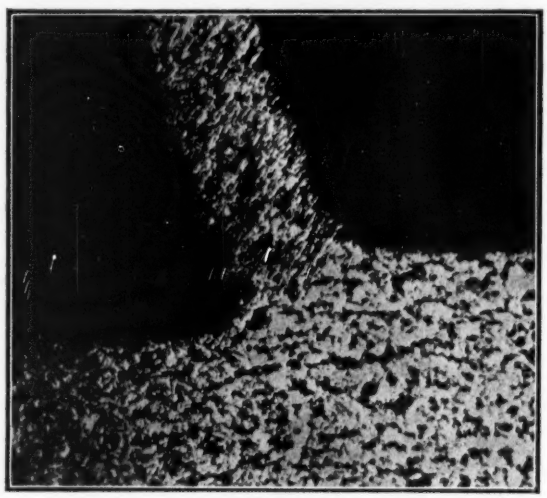

FIG 1

PURE SHEAR CUTTING

The cutting action is only about half over when the

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shear has taken place. Practically the whole of the cutting force is transmitted to the rake face through the chip after shear takes place, only a small force being involved with the clearance face. Very high pressures between chip and tool are developed, and the nascent under-surface of the chip quickly wipes the contact area of the tool extraordinarily clean, with the consequence that very high coefficients of friction

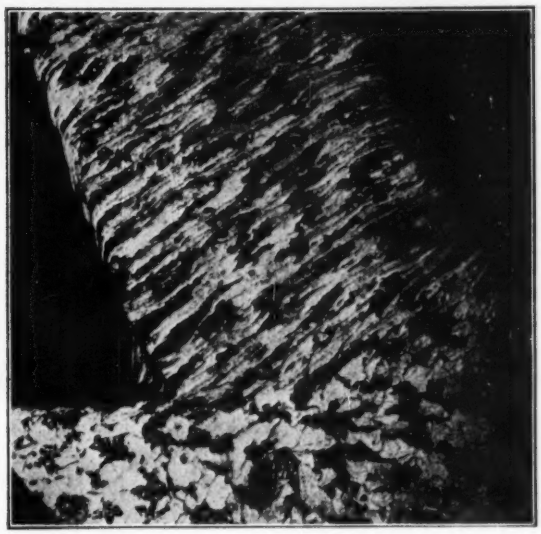


FIG 2
STEEL CUTTING WITH BUILT-UP EDGE. × 100

occur. The pressures are of the order of 100 tons/sq. in., the coefficients of friction are of the order of unity, and roughly as much energy is required to move the chip over the tool as was originally required to form it at the shear plane.

Under such chip–tool interface pressures film lubrication is quite out of the question, and the attainment of any form of friction reduction is difficult. The basic problem of the application of the lubricating function of cutting fluids is to obtain access to the area and to contaminate it in some way so as to reduce the friction.

BUILT-UP EDGE

The high friction and the high pressure cause the metallic grains in contact with the rake face to adhere to it so that they drag behind the rest of the chip. The ends of the sheared grains are further deformed into a comma-shaped tail lying nearly parallel to the rake face and they become attached to the tool. Further layers attach themselves, each becoming a little more curved until some are shaped like a turbine blade. The resulting " build up " has a characteristic triangular section which usually covers and protects the rake face adjacent to the cutting edge for a length about two or three times the distance it projects towards the approaching metal. The characteristic straticulate structure of the built-up edge is clear proof of its origin, and it kills the old conjecture that it is formed of " powder," filling the " vacuum " of a crack running ahead of the tool.

Fig 2 shows an excellent example of a built-up edge in steel cutting, and Fig 3 is a close-up of the same edge. A sheared grain of pearlite can be seen severed in two by the point of the built-up edge, one-half slowing down and becoming part of the chip, the other half continuing at the cutting speed but becoming further distorted into the comma-shaped grains characteristic of the surfaces of all machined parts.

In Fig 3 a small part of the severed grain can be seen added to the point of the built-up edge. This continues until the " build up " becomes unstable and part of it passes into the workpiece or becomes part of the chip. This growth and shedding may occur very rapidly indeed, and forms one of the major types of defect in finished surfaces. Fig 4 shows a built-up edge without the well-defined outline of Fig 3. This is because a fragment of the edge has just escaped in the work and the edge is in process of reformation.

The author has experienced several examples of abnormally large build ups leading to fracture of the tool.

DISCONTINUOUS CUTTING

Chip adhesion to the tool and release of parts of the build up may occur in a cyclic fashion, leading to a common type of continuous chip with clearly marked segments. Fig 5 shows such a case in which the cyclic action is reflected in the degree and direction of shear within each segment. In Fig 6 the action is entirely discontinuous. The scribed lines on the outer surface serve to indicate the very varied amount of shear within the segment. The variation in force due to the cutting action, a characteristic of practically all machining, reaches its maximum in this type of work. The severance of the segment relieves the tool of much of its load, and it therefore jumps elastically forward and propels the segment away from the tool, so causing the familiar rain of chips in brass and cast-iron cutting.

CRACKS AND GAPS

In certain forms of heavy cutting a transitory crack, first recorded by F. W. Taylor, runs ahead of the tool. Such cracks are formed in tension by the splitting action of the chip moving away from the parent metal in the direction of the rake face.

In discontinuous cutting a shear crack starts at the tool point and is propagated along a plane towards the surface of the work (Fig 6).

Some microphotographs show a gap between the under-surface of the chip and the part of the built-up edge remote from the cutting edge (Fig 4). These may be due to the method of taking the photograph. The fact that the maximum tool wear occurs behind

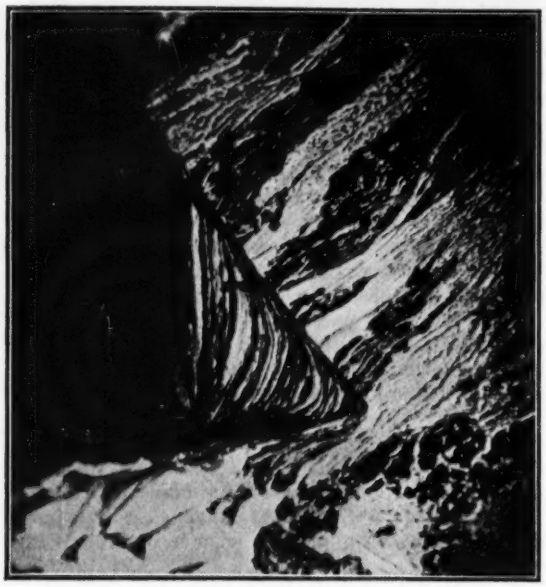


FIG 3
SAME AS FIG 2 BUT WITH MAGNIFICATION OF × 350

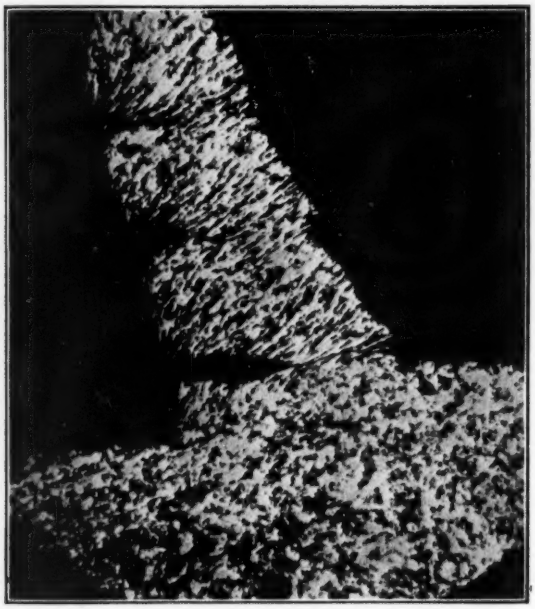


FIG 5
SEGMENTAL CUTTING

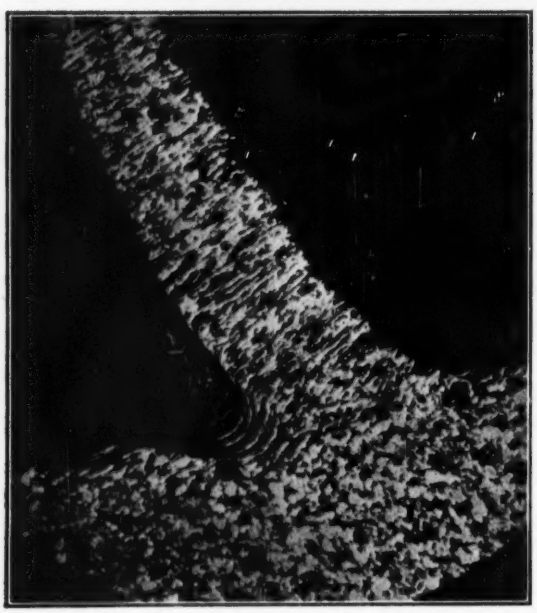


FIG 4
BUILT-UP EDGE REFORMING

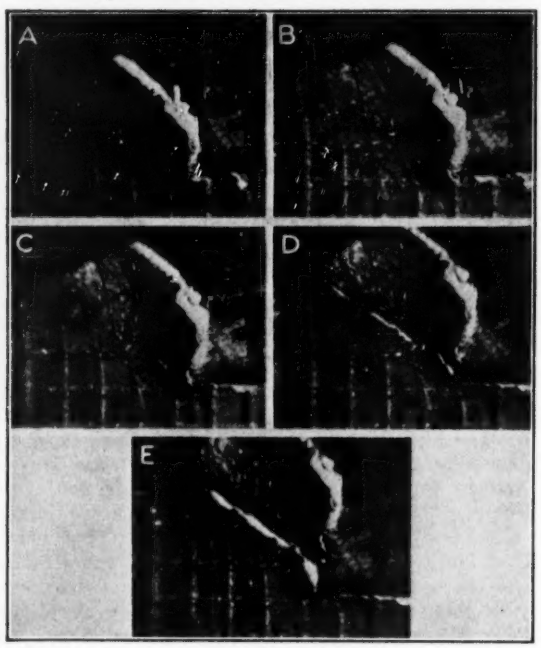


FIG 6
DISCONTINUOUS CUTTING

the built-up edge and in a region outside the volume generated by the advancing surface of the work shows that the gaps cannot exist for more than a small proportion of the cutting time.

The gross deformation almost to the point of fracture which is characteristic of metal cutting may form minute fissures, cracks, or capillaries in the metal. The author has never seen any " concrete " evidence of their existence throughout the cutting, and is of the opinion that the high compressive stress at the critical points makes the possibility rather remote.

TABLE I

Power Consumption, Pressure, and Temperature

Material cut	Brinell hardness	H.p/cu. in/min	Specific pressure tons/sq. in.	Specific heat	Density lbs/cu. in.	Adiabatic temperature rise °C
Plain carbon steel	125	0·62	109·6	0·12	0·28	435
	180	0·75	132·5			526
	261	0·90	159·0			632
Alloy steel	125	0·51	90·2	0·12	0·28	358
	180	0·62	109·6			435
	311	0·80	141·5			562
	451	1·60	283·0			1122
Free cutting steel	119	0·37	65·4	0·12	0·28	260
	185	0·47	83·1			330
	229	0·52	91·9			365
Cast-iron	110	0·22	38·9	0·13	0·26	154
	196	0·64	113·2			447
	269	1·20	212·0			837
Leaded brass	33	0·22	38·9	0·1	0·30	173
	130	0·30	53·0			236
Unleaded brass	51	0·54	95·5	0·1	0·30	424
Copper	40	0·88	155·7	0·1	0·32	648
Magnesium alloys	32	0·09	15·9	0·24	0·065	136
	68	0·11	19·4			166
Aluminium alloys						
2S — H14	32	0·12	21·2	0·22	0·1	128
11S — T3	97	0·12	21·2			128
24S — T4	122	0·19	33·6			204
14S — T6	139	0·20	35·4			214
75S — T	153	0·20	35·4			214

Dry cutting depth 0·125 inch; feed 0·0156 inch; values are for sharp tools. Multiply by two for dull tools. For 0·002 inch feed multiply by 1·4. For 0·060 inch feed multiply by 0·8.

Their existence is most probable at free surfaces. Movement on crystallographic slip planes, hundreds of molecules thick, may provide some degree of porosity in the chip. The fact that the beneficial effect of fluids is most marked at low speeds and that the effect is independent of any cooling effect is evidence that some penetration of the fluid into the heart of the cutting does occur.

CURVATURE

Chips may vary from perfectly straight lines to tightly rolled up curls for a variety of reasons. The shear plane is most nearly a true plane near the cutting edge of the tool. Its thickness increases as it approaches the work surface and there is always a small radius joining the original work surface with the outer surface of the chip. This results in a slightly different orientation of the grains, and a variation in speed between the inner and outer layers of the chip. Merchant has shown that the non-uniform stress distribution on the chip–tool interface causes a curved shear plane and therefore curvature of the chip.

The other causes of chip curvature are mainly mechanical. They are variation of cutting speed along the cutting edge as in the major edges of a drill, curved rake faces caused by the original grinding or by the development of a crater, the presence of a secondary rake face or a chip groove, the shape of chip clearance spaces, and the presence of a chip breaker.

In a perfectly straight chip the cutting pressure on the tool is high near the cutting edge, and it fades to zero a considerable distance from the edge. In a curved chip the pressure obviously becomes zero where the underside of the chip leaves the tool. As the curvature increases, the contact area is reduced, so making it more accessible to cutting fluids, but the

maximum pressure rises. The length of the contact area is commonly between two to four times the penetration, depth of cut, or undeformed chip thickness.

POWER CONSUMPTION

The mechanical energy supplied to bring about the cutting action at the desired rate practically all appears as heat energy, the surface energy of the new surface being of insignificant proportions. The heat is generated mainly at the shear plane and at the chip–tool interface, but some appears at the clearance face either at the lower face of the built-up edge, see Fig 3, or at a small worn portion of the tool of zero clearance. Because of its harmful effect on the properties of the tool, the heat is a primary factor limiting the life of the tool, so that the refrigerating effect of fluids is of importance. The ideal cutting fluid has a double effect, firstly, in improving the cutting action so as to improve surface finish and in reducing the cutting forces and therefore the heat generated, and secondly, by assisting in the removal of the heat away from the heart of the cutting and thereby sustaining the tool properties so as to lengthen its useful life.

The power consumption per unit volume cut is not greatly affected by variations of the cutting speed, it is practically independent of tool material, varies inversely with the feed, goes up with the wear of the tool, and down with an increase in the rake. The specific tool pressure is found by dividing the component of the cutting force in the direction of cutting (Fc) by the area of the underformed chip ($w_1 t_1$). It is a somewhat artificial conception because of the slope of the rake face, the variation of pressure over the chip–tool interface and because the contact area is greater than that used in the calculation. Nevertheless, it is a useful figure for reference, for comparing different metals, and for predicting the forces and power required. If it is presumed that all the power appears as heat in the chip alone, the adiabatic maximum possible temperature rise may be calculated if the density and specific heat are known. To obtain the theoretical maximum temperature the initial temperature, say 20° C, is added. In cutting at high speed the adiabatic condition is approached, and measurement of the average temperature reached by calorimeter and thermocouple methods has confirmed the approximate value of the calculated maximum.

Table I gives the hardness and power consumption for a number of materials from an American source. The author has added the columns giving specific pressure, specific heat, density, and adiabatic temperature rise. Study of the pressures and the temperatures shows the formidable problem involved in the effective application of cutting fluids.

The high temperatures reached in grinding are mostly due to the fact that the cutting is inefficient from an energy point of view, this being due to the fact that there can be little control over the sharpness and shape of the cutting edges and to their high negative rake.

The basic problem in extending the cutting speed and life of tools is that of obtaining a tool material capable of standing up to the pressures and temperatures involved. That problem has already been solved for aluminium because of the low pressures and temperatures generated. The shop term "the sky is the limit for aluminium," although not wholly true, has a sound scientific basis.

ELECTRIC EFFECTS

The intimate junction of the tool and work form the hot junction of a thermocouple. The usual low resistance of the closing circuit via the machine allows current to pass through the chip–tool interface. This effect has been used to measure the average tool temperature by a number of investigators.

A further effect which has not yet been scientifically investigated is that the high pressure, the high speed, and the high friction near the cutting point generate local potentials and currents which may have an influence on wear and life. An allied practical application of this is the "electrolytic" grinding of carbides.

INTERMITTENT CUTTING

Where a tool cuts intermittently, as in milling or shaping or when turning across a keyway, it is found that a markedly better surface finish is obtained for a small distance after the initial entry of the tool to the work. This is caused by the absence of a built-up edge due to the reduction of friction because of the contamination of the tool during its non-cutting period. The phenomena is evidence of the very short time that is required for the super cleaning of the rake face and the establishment of high friction conditions.

In all forms of intermittent cutting the idle period is valuable in allowing diffusion of heat from the tool. The application of fluids can help this diffusion and assist in freeing the tool points from adherent chips.

ACKNOWLEDGMENT

All the pictorial illustrations in this paper were taken from "Physics of Metal Cutting," by Hans Ernst, Cincinnati Milling Machine Co., Ltd., U.S.A. The power consumption figures in Table I were taken from "Machining, Theory and Practice," A.S.M.

MECHANICAL TESTING OF CUTTING OILS*

By I. S. MORTON† and R. TOURRET† (Associate Fellow)

INTRODUCTION

CUTTING oils are used to facilitate metal-cutting processes. A machining operation must produce the job from the appropriate material within the specified tolerances for dimensions and surface finish, and do so as economically as possible. A cutting oil must, therefore, help to satisfy these requirements without introducing undesirable secondary features. An ideal cutting oil would have the following properties:

Primary Properties

(*a*) Give high rate of metal removal and long tool life.
(*b*) Give good surface finish.
(*c*) Give low tool loading and power consumption.

Secondary Properties

(*a*) Cool work.
(*b*) Facilitate removal and cooling of chips.
(*c*) Have no harmful physiological effects.
(*d*) Cause no smoke or smell.
(*e*) Be non-corrosive and non-staining.
(*f*) Cause no interference with machine lubrication.
(*g*) Be non-foaming and non-gumming.

Though the secondary properties of a cutting fluid are of immense importance in the workshop, only the primary properties, *i.e.* those influencing the actual cutting operation, are considered here.

METHODS OF PERFORMANCE TESTING

The many types of metal-cutting processes, *e.g.* drilling, turning, milling, threading, grinding, and broaching, have somewhat different requirements as far as the cutting oil is concerned. In all cases, however, the cutting oil can influence the operation in respect of tool life, surface finish, and cutting force.

Of these the first is generally by far the most important, but the second is important in some cases. The force aspect is, on the whole, of little direct concern in the workshop. The cutting fluid influences performance by two main factors, namely cooling and lubrication of the tool, the relative importance of which varies greatly, not only between metal-cutting processes, but even for different examples of the same process. It is not, therefore, surprising that there has been a great deal of discussion as to how many cutting processes must be used before a reasonable overall assessment of the performance of a cutting fluid can be established.

Methods of testing the primary properties may be subdivided into three classes: workshop trials, machining tests under laboratory conditions, and simulation or bench-type laboratory tests, and these are reviewed below.

WORKSHOP TRIALS

Workshop tests have been largely relied on in the past. Their use is sometimes effective, but it is difficult to maintain the necessary close control over the many experimental variables involved. All too often the results are influenced by personal prejudice, and the secondary characteristics (notably appearance and smell) are more heeded than the cutting characteristics. However, the Royal Dutch-Shell Laboratories in Amsterdam have successfully collaborated with a manufacturer to conduct field tapping tests on a wide range of cutting oils. In this case unusually strict control is exercised on material specification, tool material, tool preparation, and operating procedure, and the general conditions are in many respects more akin to laboratory standards than to those of the majority of production plants.

LABORATORY METAL CUTTING TESTS

Large-scale Tests

Because of the difficulties of conducting satisfactory field trials, many investigators have conducted machining tests under laboratory conditions. In such tests the operation is conducted as in the workshop but with closer control of the factors influencing performance. Cutting fluid comparisons by drilling tests have been widely used (for reasons mentioned later), and Fig 1 shows the chief factors affecting the drilling operation which must be controlled if satisfactory results are to be obtained. The number of factors requiring control indicates why it is difficult to obtain results of the necessary precision from the ordinary workshop.

Drilling

The use of drilling for such large-scale tests was started some ten years ago in collaboration with the Research Department of the Institution of Production Engineers (later P.E.R.A.—the Production Engineering Research Association). At that time the main interest lay in tool life under roughing conditions, and drilling was chosen because it was thought that (provided only shallow holes were drilled) the results would be generally representative of all roughing

* MS received 2 February 1954.

† The Shell Petroleum Co. Ltd.

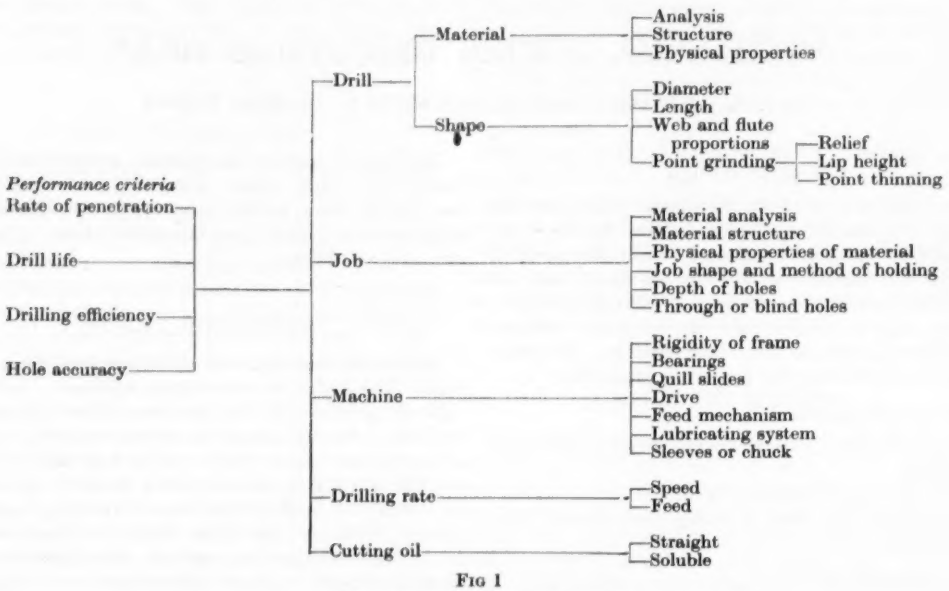
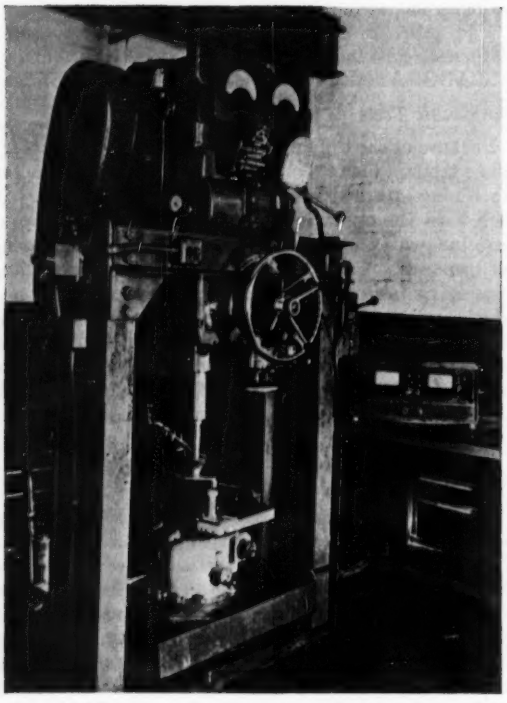
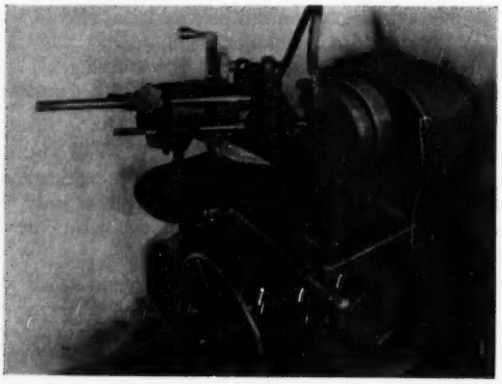


FIG 1

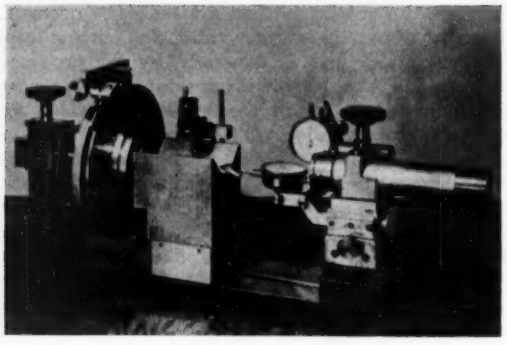
CHIEF FACTORS AFFECTING DRILLING



(*a*) DRILLING MACHINE AND DYNAMOMETER



(*b*) DRILL GRINDER



(*c*) DRILL POINT TESTER

FIG 2

P.E.R.A. APPARATUS USED FOR DRILLING TESTS

operations, including turning. Also, drilling had the attractions of a standardized type of tool and the use of a moderate amount of material, and it was fairly straight-forward to develop the necessary controls. The procedure used has been fully described elsewhere,[1] and Fig 2 shows some of the equipment

The results of a later series of tests are shown in Table II. Fig 3 gives the mean drill life for each oil, and indicates where apparent differences were statistically significant (at 5 per cent level). The experimental oils tested in this case were similar to regular cutting oils, and the general standard of

TABLE I

Early Comparison of Cutting Fluids by Drill Life Tests

Test conditions :

Drills used : ¼-inch dia commercial (wartime " 66 " H.S.S.) quality
Material drilled : 0·25 per cent C, 0·65 per cent Mn axle steel (blanks cut from discarded locomotive axles and normalized before use)
Speed : 650 r.p.m., 106 s.f.p.m.
Feed : 0·014 inch per rev., 9·1 inches per minute
Depth of hole : 1¼ inches

Oil number	Composition of oil	Number of holes drilled before failure	Average number of holes	Min. torque, lb ft	Min. thrust, lb	Remarks
1	Oil 9 + 5% wt sulphurized fat A	108, 84, 80, 94	92	22·5	1500	Very smooth cutting with little variation in torque and thrust.
2	Oil 7 + 0·8% wt added sulphur	65, 81, 72, 74	73	20	1600	Smooth cutting, with small variations in torque and thrust.
3	Oil 9 + 5% wt chlorinated hydrocarbon	42, 51, 54, 47	48	23	1750	Smooth cutting, with small variations in torque and thrust.
4	Oil 9 + 0·2% wt added sulphur	33, 35, 41, 41	37	22·5	1600	Smooth cutting, with small variations in torque and thrust.
5	Oil 7 + 0·2% wt added sulphur	33, 37, 30, 35, 12 *	34	22	1500	Smooth cutting, but rather greater variations in torque and thrust.
6	Oil 9 + 2% wt pine oil	30, 32, 24	29	28·5	2200	Fairly smooth cutting, but greater variations in torque and thrust.
7	Blend of 350 Flash mineral oil (Pool 8) + technical white oil (Pool 30) to viscosity of Oil 9	24, 26, 12,† 18, 27	24	30	1650	Rough cutting, with large fluctuations in torque and thrust from hole to hole and during individual holes.
8	Oil 9 + 3% wt fatty acid	22, 18, 17, 24, 29	22	30	2250	Rough cutting and much noise also large fluctuations in torque and thrust.
9	Solvent extracted mineral oil, of viscosity 65 sec Red. I at 140° F	15, 2,‡ 13, 16	15	24·5	1750	Cutting smoother than with Oils 7 and 8, but large rise in torque and thrust towards end of each hole, with tendency for drill to bind on withdrawal.

Notes : Torque and thrust were measured for each hole. Drill failure was indicated by rise in torque readings and confirmed by examination of drill. All failures were at outer corners of drill.

* Premature failure of outer corners.
† Drill lip severely chipped.
‡ Point collapsed completely.
} Results not more than 50 per cent of mean discarded. Scatter of results probably due to use of wartime materials.

used. A typical early set of results is given in Table I (which refers to a range of experimental oils rather than commercial cutting fluids). The test showed quite clearly an influence from the various additives and gave some indication of their relative merits. Thus the comparatively poor performance of straight mineral oils was indicated by the performance of Oils 7 and 9, and the advantageous effect of added sulphur was shown by Oils 2 and 5, and of sulphurized fat by Oil 1. The benefit of a chlorinated hydrocarbon was shown by Oil 3.

performance was thus high. Many of the results supported existing beliefs on the behaviour of the cutting oil components concerned, but there are some interesting features to which attention might be drawn. Thus the particular chlorinated hydrocarbon used impaired performance instead of improving it, as shown by comparing Oils 15, 16, and 17. This surprising result has since been confirmed in other trials, but it should be emphasized that such results are not necessarily typical of all chlorinated hydrocarbons. There are also considerable differences in

the performance of oils of similar constitution but blended with alternative sulphurized bases, as shown by the results for Oils 15, 19, and 20. Thus valuable information is obtained by this type of testing, since the results with Oils 12 and 16, is noteworthy, as is also the superiority of the sulphurized fat used in Oil 11 to the sulpho-chlorinated fatty oils in blends 14 and 18. Oil 13 was introduced because the

TABLE II

Typical Comparison of Cutting Fluids by Fully Developed Drill Life Tests

Test conditions :

Drills used :	¼-inch dia H.S.S. manufactured to special limits
Material drilled :	0·6 per cent C, 0·65 per cent Mn tyre steel to B.S. 328
Speed :	845 r.p.m., 138 s.f.p.m.
Feed :	0·014 inch per rev., 11·8 inches per minute
Depth of hole :	1¼ inches

Oil number	Composition of oil	Number of holes drilled before failure	Average number of holes	Remarks
11	65% wt sulphurized mineral oil X 25% wt sulphurized fat B 10% wt light distillate	148, 140, 124, 126	135	Smooth cutting with little variation in torque and thrust. Strong odour with some smoke. Failure by land wear.
12	63% wt sulphurized mineral oil X 25% wt sulphurized fat C 10% wt light distillate 1·5% wt chlorinated hydrocarbon 0·5% wt fatty acid	136, 126, 98, 102	116	Smooth cutting with little smell or smoke. Failure at outer corners.
13	65% wt sulphurized mineral oil X 35% wt rape oil	118, 84, 110, 89	101	Unusual consistent torque and thrust until last hole. Smooth cutting with little smell or smoke. Failure at lands.
14	65% wt sulphurized mineral oil X 25% wt sulphurized and chlorinated fatty oil D 10% wt light distillate	85, 87, 78, 81	82	Smooth cutting but accompanied by heavy white smoke. Some corrosion of machine. Failure at outer corners.
15	65% wt sulphurized mineral oil X 25% wt sulphurized fat C 10% wt light distillate	90, 87, 46, 82	79	Cutting initially smooth but deteriorating later. Some smoke and smell with black deposit on drill. Failure mainly at outer corners.
16	63·5% wt sulphurized mineral oil X 25% wt sulphurized fat C 10% wt light distillate 1·5% wt chlorinated hydrocarbon	62, 52, 83, 72	68	Satisfactory cutting with negligible smoke and smell. Failure mainly at outer corners, but accompanied by wear at the chisel edge.
17	55% wt sulphurized mineral oil X 25% wt sulphurized fat C 10% wt light distillate 10% wt chlorinated hydrocarbon	44, 43, 69, 40	50	Satisfactory cutting, but more smoke and odour with corrosion of machine spindle overnight.
18	65% wt sulphurized mineral oil X 25% wt sulphurized and chlorinated fatty oil E 10% wt light distillate	68, 43, 38, 36	47	Smooth cutting with little smoke and negligible smell. Failure due to outer corner wear accompanied by cratering at chisel edge.
19	65% wt sulphurized mineral oil Y 25% wt sulphurized fat C 10% wt light distillate	46, 50, 38, 28	41	Cutting soon became harsh with much variation in torque readings. Some smoke, but little smell. All drills failed finally at the chisel edge, preceded by blunting of the outer corners.
20	65% wt sulphurized mineral oil Z 25% wt sulphurized fat C 10% wt light distillate	47, 26, 38, 42	39	Rough cutting with rather more smoke and smell than with Oil 19. Failure at chisel edge. Some evidence of gumming.

Notes : Torque and thrust were measured for each hole. Drill failure was indicated by rise in torque readings, and confirmed by examination of drill. Speed and feed were chosen to give drill failures at outer corners as far as possible, but this was not always obtained.

such differences in performance could not have been predicted from theoretical considerations, and are unlikely to be shown up by other laboratory tests.

The beneficial effect of fatty acid, as indicated by inclusion of rape-seed oil is popularly supposed to give excellent performance, and indeed the cutting was unusually smooth with consistent torque and thrust, and little smell or smoke. It can therefore be

realized why such an oil can make a good impression on workshop staff, though, in fact, its performance is substantially below the best.

The tests so far described have all referred to straight oils, but drilling tests have also been useful in discriminating between different soluble oils, as shown in Table III, which refers to a comparison of a conventional soluble oil with two E.P. soluble oils. The same table includes results from a smaller drilling test referred to later.

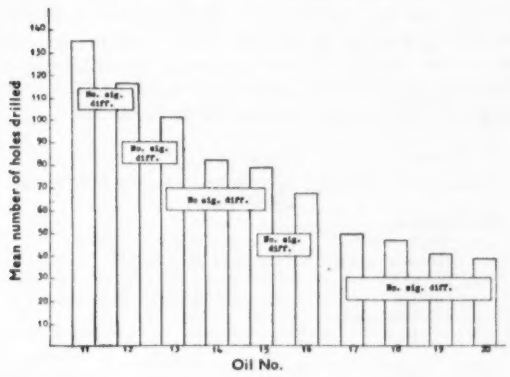


FIG 3

BLOCK DIAGRAM OF MEAN DRILL LIFE RESULTS FROM TABLE II, INDICATING SIGNIFICANT DIFFERENCES (AT 5 PER CENT LEVEL)

TABLE III

Comparison of Two E.P. Soluble Oils with a Conventional Soluble Oil by Drilling Tests

Test conditions :

	Large drill test	*Small drill test*
Drills used :	$\frac{3}{8}$-inch dia H.S.S. selected	$\frac{1}{4}$-inch dia H.S.S. selected
Material drilled :	Tyre steel to B.S. 328	Tyre steel to B.S. 328
Speed :	1070 r.p.m., 175 s.f.p.m.	4000 r.p.m., 260 s.f.p.m.
Feed :	0·10 inch per rev. 10·7 inch per minute	approx. 20 inches per minute
Depth of hole :	$1\frac{1}{4}$ inches	$\frac{1}{2}$ inch

Oil	Number of holes drilled before failure	
	Large drill test	Small drill test
Conventional soluble oil	25, 62, 50, 61 Average 47	130, 64, 106 Average 94
E.P. soluble oil A	90, 131, 174+,* 174+ * Average 137+	196, 98, 101 Average 126
E.P. soluble oil B	158, 174+,* 133, 174+ * Average 159+	258, 143, 158 Average 187

* Considerable wear at 174 holes, though failure not complete. Tests discontinued, since superiority over conventional oil clearly established.

Other Operations

Large-scale investigations have been extended to turning and tapping, and the P.E.R.A. equipment used is shown in Figs 4 and 5.

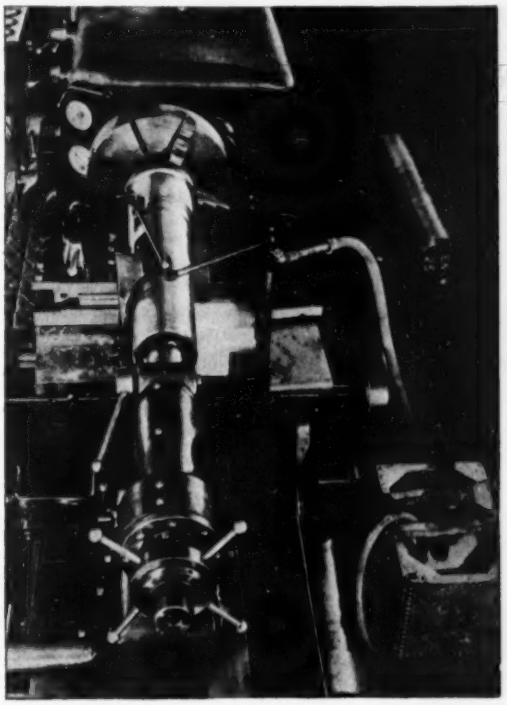


FIG 4

P.E.R.A. HEAVY LATHE USED FOR TURNING TESTS

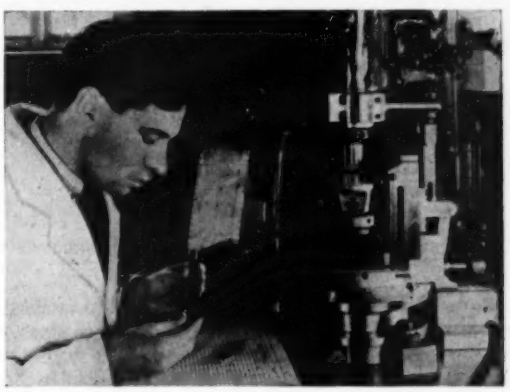


FIG 5

P.E.R.A. EQUIPMENT FOR TAPPING TESTS

In the turning test some success was obtained in selecting cutting conditions which enabled both tool life and surface finish measurements to be made. Tests of this type are still continuing, but it appears

so far that tool life tests with straight cutting oils generally line up quite well with the drill life tests (thus verifying the assumption made at an earlier stage). Some interesting general data indicate that, as tool life increases, surface finish deteriorates.

Small-scale Tests

The tests so far described have been very useful, but, in view of their scale, are expensive in time and money. Accordingly, tests are being devised at Thornton Research Centre which, though less precise because they are on a smaller scale and because of unavoidable limitations on the control of tools and material, are considered to be satisfactory for the preliminary sorting out of potential cutting fluids.

Drilling

A small drilling machine (Fig 6) has been modified by the provision of a constant-weight feed for standardized drill-life tests. By arrangement with a drill manufacturer, selected $\frac{1}{4}$-inch dia drills are used,

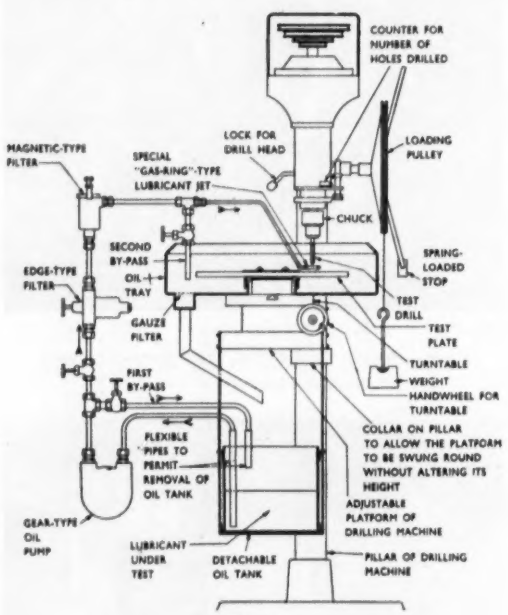


FIG 6

"PACERA" DRILLING MACHINE SET UP FOR DRILLING TESTS

and plate material is used for workpieces to facilitate indexing on a rotating fixture. The drills are checked for accuracy of point grinding before use. No dynamometer is used, since such is considered to give no useful information (see Cutting Force Measurements), and it has been found satisfactory to drill to complete point failure, even though this means using a new drill for each test.

Typical test results are shown in Table IV, from which it will be seen that the test discriminated satisfactorily between various soluble oils and straight cutting oils. Thus the desirability of having some lubricating action in addition to cooling was shown up in the comparison between water and the soluble oils, and the benefits of using an E.P. type of soluble oil were also indicated. In the case of the straight cutting oils the results were again sufficient to pick out the influence of the different constituents. So far results obtained have generally been similar to those obtained in the larger scale tests, as shown, for example, by the results included in Table III.

TABLE IV

Comparison of Straight and Soluble Cutting Oils by Small Drilling Test

Test conditions :
Drills used : $\frac{1}{4}$-inch dia H.S.S. selected
Material drilled : Tyre steel to B.S. 328
Speed : 4000 r.p.m., 260 s.f.p.m.
Feed : approx. 20 inches per minute
Depth of hole : $\frac{1}{2}$ inch

Oil	Number of holes drilled before failure	Average number of holes
Tap water	18, 22, 52, 29, 23, 31	31
Conventional soluble oil	78, 74, 72, 54, 69, 43	65
E.P. soluble oil	113, 104, 123, 119, 131, 101	115
Compounded oil	58, 146, 68, 47, 92, 88	78
Inactive sulphurized oil	176, 140, 124, 138, 93, 183	139
Active sulphurized oil	161, 180, 190, 146, 150, 166	165

TABLE V

Comparison of Four Straight Oils by Tapping Tests

Tapping conditions :
Taps : $\frac{1}{4}$-inch B.S.F., selected
Material tapped : EN1 Bright drawn mild steel bar, $\frac{3}{8}$ inch thick
Core size : 0·260 inch
Speed : 580 r.p.m., 47·5 s.f.p.m.

Composition of oil	Number of holes tapped before tap failure	Average number of holes
10% sulphurized fat + 3% chlorinated hydrocarbon + $\frac{1}{4}$% sulphur + $\frac{1}{2}$% fatty acid + 86% mineral base	202, 298	250
10% sulphurized fat + $\frac{1}{2}$% sulphur + $\frac{1}{2}$% fatty acid + 89% mineral base	39, 112, 32	say, 60
10% sulphurized fat + $\frac{1}{2}$% fatty acid + 89·5% mineral base	14, 41, 12	say, 22
10% alternative sulphurized additive + $\frac{1}{2}$% fatty acid + 89·5% mineral base	2, 1, 1	say, 2

Other Operations

Work has been started on a small tapping test, using $\frac{1}{4}$-inch B.S.F. taps to tap nut blanks. The

TABLE VI

Comparison of Cutting Oils by Lathe Tool-life Tests

Test conditions :

Tool material :	$\frac{1}{2} \times \frac{1}{2}$-inch high-speed steel
Tool shape * :	0–7–5–5–7–0–$\frac{1}{16}$
Test material :	S.80B high-chrome steel
Cutting speed—Rotational :	400 r.p.m.
Surface :	105 to 67 f.p.m.
Feed :	0·014 inch per rev.
Depth of cut :	0·060 inch

Lubricant	Test number	Number of work-pieces turned (including the one on which failure occurred)	Weight of metal removed before failure, grams	
			Per test	Geometric mean
Soluble oil (1 : 15v)	1	5	1818	2380
	2	5	1778	
	3	8	3088	
	10	8	3214	
Compounded oil	4	8	3212	1561
	5	3	1066	
	6	2	472	
	11	9	3667	
Active sulphurized oil	7	3	1152	1177
	8	2	823	
	9	6	2142	
	12	3	945	

* Expressed in accordance with the convention whereby the back rake, side rake, front clearance, side clearance, trail, and approach angles are listed, in degrees, in that order, followed by the nose radius in inches.

results of some preliminary tap-life tests are given in Table V, and indicate the influence of various components quite clearly. It is particularly interesting to compare the beneficial effect of the particular chlorinated hydrocarbon used in this case with the detrimental influence of another type as shown by drilling tests (Table II) and other tapping tests not here quoted.

A certain amount of lathe tool-life and surface-finish testing has been done to answer specific queries, and the results of typical comparisons are shown in Tables VI and VII.

Cutting Force Measurements

So far no mention has been made of the third factor included under "primary properties," *i.e.* cutting forces. It has frequently been thought that relatively brief tests with appropriate tool dynamometers should give an indication of the effect of cutting fluid on tool-life performance. Since the cutting forces depend to some extent on the friction involved in the cutting action, and since generation of heat, which is a principal factor in the destruction of the tool, depends on the work done at the tool point and is related to the cutting forces, it therefore seemed reasonable to suppose that cutting forces should bear some relation to expected tool life, *i.e.* that the cutting fluid giving a minimum cutting force would give the longest tool life. In our experience this has not, however, been the case; thus in Table I there is no relation between tool life and thrust on the drill, and while there is some tendency for the torque to rise as drill life becomes shorter, there are sufficient exceptions, *e.g.* Oils 9 and 2, to show that this could not be relied on.

Such results have also been obtained in general machinability testing. A study of the cutting process with dynamometers and subsequent analysis of the results should lead the way to a better understanding of metal cutting, and therefore indicate lines along

TABLE VII

Comparison of Cutting Oils by Lathe Surface-finish Tests

Test conditions :

Depth of cut, roughing :	0·100 inch
,, finishing :	0·010 inch
Feed, roughing :	0·011 inch per rev.
,, finishing :	0·0045 inch per rev.
Speed, for low-carbon steel :	450 r.p.m.
,, DTD 49B alloy steel :	280 r.p.m.
,, Duralumin and gun metal :	800 r.p.m.
Tool shape, for low-carbon steel :	10–12–8–6–8–0–$\frac{1}{16}$
,, DTD 49B alloy steel :	8–10–6–6–8–0–$\frac{1}{16}$
,, Duralumin :	30–20–8–8–8–0–$\frac{1}{16}$
,, gun metal :	0–0–12–12–8–0–$\frac{1}{16}$
Results :	Range of two or more "Talysurf" h_{ave} meter readings, microinches

Test metal	Roughing operations				Finishing operations			
	Active sulphurized oil	Non-active sulphurized oil	Compounded oil	Soluble oil (1 : 15 v)	Active sulphurized oil	Non-active sulphurized oil	Compounded oil	Soluble oil (1 : 15 v)
Low carbon steel (average hardness 202VHN) . .	170 to 180	170 to 180	>200	>200	70 to 90	80 to 110	100 to 120	100 to 130
DTD 49B alloy steel (average hardness 264VHN) . .	100 to 120	90 to 120	100 to 120	120 to 150	25 to 30	25 to 30	20 to 26	28 to 30
Duralumin . .	100 to 120	100 to 120	100 to 120	100 to 140	60 to 65	60 to 65	60 to 65	60 to 70
Gun metal . .	75 to 80	75 to 80	75 to 80	75 to 90	45 to 50	45 to 50	45 to 50	45 to 50

which cutting fluids might be improved. Nevertheless, despite the immense amount of work which has been done in the past ten years (which has undoubtedly increased our understanding of cutting fluid requirements), there appears to be no substitute for tool life and surface finish tests when it comes to the selection of cutting oils for commercial purposes.

TABLE VIII

Results of Four-ball Tests on Cutting Oils Listed in Table I

Oil number	Average number of holes drilled before failure	2½ sec seizure delay load, kg	Welding load, kg
1	92	103	195½
2	73	(a)	(a)
3	48	136	195½
4	37	102	161
5	34	(a)	(a)
6	29	57	85
7	24	(a)	(a)
8	22	63	85
9	15	59½	93½

(a) Results not available.

SIMULATION OR BENCH-TYPE TESTS

Experience with laboratory inspection tests of cutting fluids by means other than actual metal-cutting has been largely unrewarding. The Shell four-ball machine[2,3,4] has been useful for making a first selection of E.P. additives and for the control testing of current production materials. The results in Table VIII show that the better oils have high 2½-sec seizure-delay and weld load figures, but there is no relationship suitable for general application. Table IX gives the four-ball machine results obtained on the cutting oils referred to earlier in Table II, and it will be seen that this machine did not show up important differences in cutting performance, *e.g.* between the different sulphurized base oils (cf. Oils 15, 19, and 20).

Since cutting oil performance is so bound up with E.P. agents, and in particular with the inclusion of sulphur and chlorine, it has become usual practice to measure percentage of sulphur and chlorine and obtain their release figures for cutting oils. A typical set of figures is given in Table X. These again refer to the cutting oils in Table II, and show that there

TABLE IX

Four-ball Machine Test Results—Various Parameters Compared with Drilling Test Results (Table II)

Test conditions :

Speed : 1500 r.p.m.
Oil temperature : ambient

Oil number :	11	12	13	15	16	17	18	19	20
Tool life, average number of holes drilled	135	116	101	79	67	50	47	41	38
Lines indicate where there is no significant difference between the results									
Load at first seizure, kg	60	73	72	62	67	70	84	61	64
Zero delay load, kg	180	140	150	140	150	210	140	110	130
2½ sec seizure load, kg	82	73	80	91	77	100	98	90	83
Welding load, lb	631	501	562	631	562	631	794	501	794
Mean Hertz Load, kg	79	70	77	77	75	77	76	71	79
Wear scar, dia mm :									
At 100 kg	0·62	0·67	0·60	0·61	0·63	0·59	0·57	0·64	0·61
At 140 kg	0·87	0·98	0·92	0·87	0·87	0·86	0·96	0·92	0·87

TABLE X

Results of Chemical and Physical Tests

Oil number :	11	12	13	14	15	16	17	19	20
Tool life, average number of holes drilled	135	116	101	82	79	68	50	41	38
Lines indicate where there is no significant difference between the results									
Sulphur, % wt	5·52	3·85	1·88	3·83	3·58	3·69	3·54	3·31	3·82
Chlorine, % wt	0	0·51	0	(a)	0	0·58	3·54	(a)	(a)
Sulphur release at 100° C, % wt	0·78	0·88	0·82	1·00	1·08	0·98	1·16	0·62	1·20
Sulphur release at 200° C, % wt	1·88	1·78	1·14	2·84	1·94	1·94	2·00	1·74	2·62
Viscosity, Red. I at 140° F	119	70	68	129	67	69	71	77	75

(a) Results not available.

was no clear relationship between total sulphur or total chlorine figures, or the release figures at 100° and 200° C, and the practical performance as measured by drilling tests.

CONCLUSIONS

Chemical analyses and tests on bench-type apparatus afford only limited guidance on the mechanical performance of cutting oils. So far actual metal cutting trials (and particularly tool-life tests) have proved essential, and fortunately a limited selection of these appears sufficient for a general assessment. Considerable success has been achieved through the use of drilling and tapping tests, and resulting changes in formulation have led to improved performance at lower costs. Though such cutting tests are best done on large-scale equipment, it is practicable to obtain initial ratings, for sorting purposes, on small-scale rigs.

ACKNOWLEDGMENTS

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SATISFACTORY RECORDS ARE ESSENTIAL TO THE ECONOMIC APPLICATION OF CUTTING FLUIDS*

By H. GRISBROOK

INTRODUCTION

RESEARCH workers have carried out highly successful work in analysing cutting and friction forces and the interaction of the cutting fluid to reduce these values. They have shown the advantages to be gained by employing E.P. additives, and determined special lubricants for machining particularly difficult materials.

The cutting fluid suppliers have responded as far as is commercially possible, and it is unquestionable that improved metal working fluids are now available.

However, it is often suggested that the user has failed to take advantage of the laboratory successes and, while this is partly true, it is not always appreciated that the user has very good reasons for this apparent indifference.

It may be that he needs only relatively small quantities of fluids for certain special requirements closely analogous to the conditions promoted in the laboratories, but on the other hand he may use very large quantities on general classes of work where the conditions are more complex.

So long as he is directly concerned with single operations such as drilling, tapping, broaching, heavy roll turning, etc., he can take direct advantage of the laboratory recommendations; but when he is confronted with the requirements of capstan, turret, or automatic lathes, where one fluid has to satisfy the requirements of single point turning, forming, screwing, tapping, and reaming, then he must inevitably compromise.

In addition, his machines are not all modern, the old and the new stand side by side in his workshop, and only a limited number are capable of taking advantage of the higher speeds which can justify the expense of quality oils. The older machines can gain only a little by the use of these oils, and it is not an economic proposition. So again, he must compromise. The number of varieties of fluids available from any one manufacturer, each variety, having its particular application, serves only to confuse the issue. To quote from one supplier's catalogue, there are seven types of soluble oil, and the "neat" or "straight" oils are divided into six classes, *e.g.*:

(*a*) pure fatty oils;
(*b*) mixtures of fatty and mineral oils;
(*c*) fatty oil plus organic solvents;
(*d*) straight mineral oils;
(*e*) sulphurized oils; and
(*f*) sulpho-chlorinated oils.

The list becomes alarming to the user when he realizes that each class has its range of varieties, for instance, there are five in each of the sulphurized and the chlorinated.

So the research worker has determined the right compound for the job, and when that particular job becomes the urgent problem of the user, the oil manufacturers, when called in, have a simple problem to solve.

But it is not a practical proposition for the user to stock a large variety of oils, even though he may be using 400 to 500 brl of oil a year, he must reduce his varieties to a workable minimum. The very fact that a multi-tool operation demands a compromise does, in itself, lead to a reduction in the number of

* MS received 15 January 1954.

oils required, and it has become a practice to reduce the varieties to one or two solubles and two or three straight oils. He may, for instance, decide to have 400 brl of a standard quality of oil at 4*s*. per gal and 70 brl of a high quality oil at 7*s*. per gal. This practice can, and frequently does, reduce the effectiveness of the good work of the research laboratories.

While this is in some measure inevitable, considerable improvement could be made if the users would take more advantage of the valuable information available from the laboratories and keep consistent records when they meet a problem, and proceed to apply the information. How then should the user proceed? The problem calling for investigation will have arisen when a particular operation, in a sequence of operations, is proving unsatisfactory. Either the finish is below requirements, or size can not be maintained, or tool life is too short, etc. The fault has been measured, as otherwise the problem would not have arisen, but, for purposes of investigation, it will need to be measured much more accurately.

MEASUREMENTS TO RECORD

The choice of units and instruments for this measurement will require careful consideration. Surface finish can obviously be measured on the Talysurf, for instance. Size may be measured satisfactorily by micrometer, or other more sensitive measuring instrument, as demanded by the limits on the job, but certainly not by a GO and NOT-GO gauge. Tool life is an example where consideration of the units is particularly important. It is usual to expect a tool life which avoids breaking down the set-up during a shift. This time unit is too large to determine the relative merits of different lubricants.

Tool wear is progressive, tool failure is abrupt and cannot be awaited to arrive part way through a shift. However, total tool life is largely a question of how much must be ground away to resharpen the tool, and it can be a greater economy to regrind after one shift rather than push the tool to its limit in covering two shifts. Hence the amount of metal removed in resharpening can form a basis for estimating the effectiveness of the lubricant.

In such investigations, where proprietory brands of small tools, such as drills and taps, are concerned, it will also be necessary to check the dimensions, finish, and forms of the web, flute, etc., as these have been known to vary considerably between different manufacturers' products.

Records should be made on these lines of measurements of the work and tool's reactions to the changes in cutting compounds under test; always the objective being to ensure that the records taken are the result of the change in the lubricant and not to some extraneous element not included in the list of measurements.

The above procedure has assumed that the best possible conditions have previously been provided for the tool, machine set-up, the machine, and the quantity and direction of the delivery of the lubricant.

This latter point has recently been receiving attention in the laboratories, and is proving particularly important. It is the joint responsibility of the machine tool makers and the user; the former to ensure that the right quantity is available within the area of application, and the user to make provision for it to be delivered effectively.

It can be futile to flood the work with copious quantities of fluid in the hope that some of it will find its way to the source of heat generation. There is the example of the parting-tool operating dry, in its narrow groove, because the centrifugal action of the work has effectively diverted the fluid from the cutting edge. Drilling and boring operations are often only hopefully provided for. The objective of the investigation will be to decide whether it is an economical proposition to :

(*a*) continue with the existing cheaper grade;
(*b*) to use the existing high quality oil;
(*c*) introduce an additional grade; or
(*d*) develop a new method of application.

The introduction of a new grade emphasizes the necessity to know how well the original oils are meeting the requirements of the work on which they are being used. Is the most economical selection being made, and will it be affected by the new introduction?

When the job is running apparently satisfactorily, with the original grade, then any advantage to be gained from a change of oil must be mainly in increased production. This must result from increased speeds and feeds combined with satisfactory tool life. Here again a knowledge of the degree of tool wear, in relation to the proposed increases in speed, becomes necessary.

Records of the depth of metal removed to resharpen the tool, for each combination of speed, feed, and cutting oil, can indicate which is the most economical cutting oil for the job. What is most important is that effective records must be kept, if satisfactory selection is to be made from the wide variety of oils available. It is when such information is available that the laboratories can decide whether they are pursuing their inquiries along lines most suitable for practical application to production.

In conclusion, it is necessary to refer to the very urgent and profitable subject of straight oil reclamation from swarf. If a company is not at present taking advantage of reclamation, it will be sufficient to mention that 80 to 90 per cent of recovery is claimed, so that, at a conservative estimate, 60 to 70 per cent can be obtained.

THE EVALUATION OF CUTTING FLUIDS WITH SPECIAL REFERENCE TO PRACTICE IN THE U.S.A.*

By A. J. CHISHOLM †

SYNOPSIS

The paper is a review of methods used in the U.S.A. for the evaluation of cutting fluids. After discussing the manner in which the lubricating and cooling properties may affect the cutting process and the practical effects of these on such factors as surface quality and tool wear, various methods for evaluating the lubricating properties and the wear-reducing properties of cutting fluids are described. The reproducibility of the results and the validity of some of these methods are discussed.

INTRODUCTION

THE variety of functions which cutting fluids are required to perform indicates that the search for a single evaluation test is almost certainly hopeless; but a small number of tests, properly interpreted, may enable reasonably accurate forecasts of performance to be made.

The value of a laboratory test is often judged by comparing its results with ratings obtained in the field, but many field ratings are obtained under poorly controlled conditions and are not satisfactory standards. However, some cutting fluid manufacturers carry out evaluation tests in outside machine shops in which machining conditions are carefully controlled and data on tool grinding costs and other relevant factors are maintained over long periods; tests such as these can give valuable and valid results.

One criterion of evaluation which has been suggested is the sales volume of each individual cutting fluid; this may be useful from the business point of view, but does not satisfy the production engineer.

THE ACTION OF CUTTING FLUIDS

It is well established that when cutting fluids act as lubricants, they do so as pure boundary lubricants, and function as a result of the formation of solid-film lubricants formed by chemical reaction at the clean metal surfaces of the chip and tool [1] (Fig 1).

Lauterbach and Ratzel [2] at the Armour Research Foundation have recently shown that a cutting lubricant penetrates to the chip–tool interface from the wedge-shaped space between the flank face of the tool and the cut surface, or from the sides of the flowing chip, but they do not penetrate from the rake crevice in the opposite direction to the flow of the chip. In these experiments drops of lubricant to which a highly fluorescent material had been added were placed in different locations during cutting tests, and the distribution of the lubricant material, on the chip, tool, and workpiece was examined. The spread of the lubricant could also be observed from the way in which it affected the smoothness of the cut surfaces and the under-surfaces of the chips.

Lauterbach [3] in later experiments showed that in a turning operation, if the cutting fluid was applied between the flank face of the tool and the workpiece, the tool life could be increased appreciably. Pigott

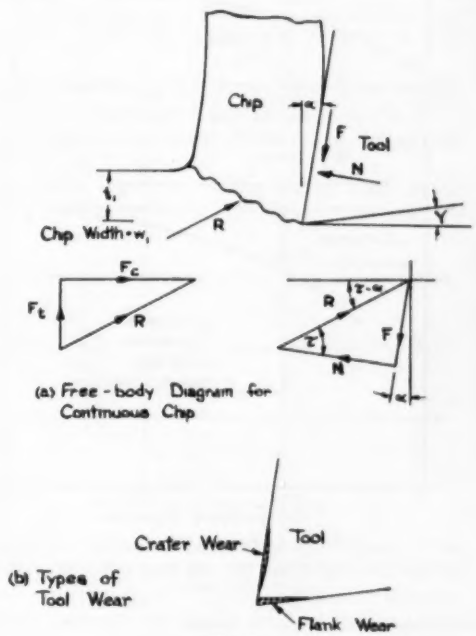

FIG 1

THE ORTHOGONAL CUTTING PROCESS

R = Resultant cutting force
F = Friction force
N = Normal force
α = Rake angle
τ = Friction angle

and Colwell [4] have also used this fact in the Hi-jet system of applying cutting fluids; in this the cutting fluid is delivered at a high velocity to the flank face crevice. Significant increases in tool life have been found when using this technique. Since this method of application enables the fluid to penetrate to the chip–tool interface more effectively, a chemically

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† The author has recently spent a year as Mechanical Engineering Liaison Officer at the U.K. Scientific Mission in Washington.

active cutting fluid can actually wear the tool more rapidly.

The important effect of cutting speed on the action of cutting fluids is illustrated in Fig 2; the curves show how the reduction in cutting force and the angle of friction at the chip–tool interface caused by a lubricant diminish as the cutting speed rises. This may be caused by the increased difficulty experienced by a lubricant in getting to the interface as the cutting

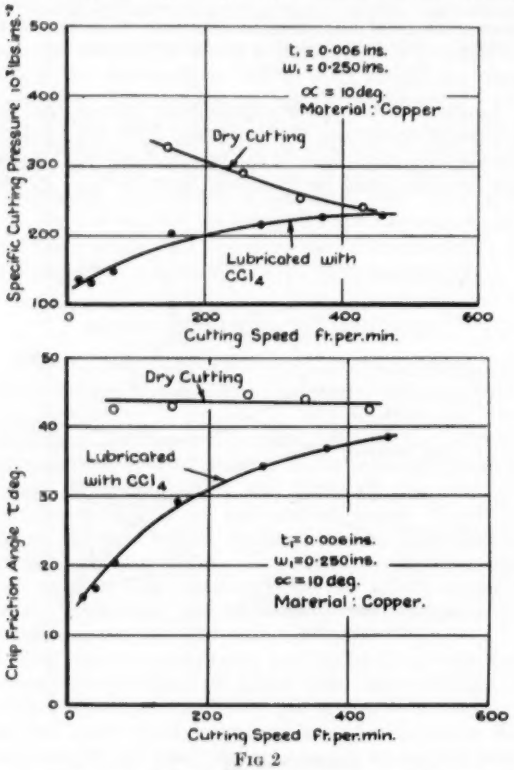

FIG 2

EFFECT OF CUTTING SPEED ON CHIP FRICTION AND CUTTING FORCE

speed rises, or it may be caused by the reduction in the lubricating properties of the solid films at the interface when the temperature rises.

PRACTICAL EFFECTS OF THE LUBRICATING PROPERTIES OF A CUTTING FLUID

Cutting speed has a very important effect on the behaviour of cutting fluids in practical machining operations. In relatively slow-speed machining operations in practice, *e.g.* tapping, screwing, and broaching, cutting fluids have important lubricating functions, but in continuous high-speed cutting operations the lubricating effects are probably slight. In intermittent cutting operations, however, such as milling and grinding,[5] in which the lubricant film on the cutting edges is replenished before each cut, lubrication may have an important effect.

A lubricant does not lower the temperature at the chip–tool interface in proportion to the change in the chip friction coefficient because the chip velocity increases as well, and the work done in friction therefore tends to remain constant, despite the reduction in the friction coefficient. If a net reduction in the temperature does occur, a reduction in tool wear may follow.

Some cutting fluids containing extreme pressure additives may reduce wear on account of the effective protective films which are formed at the rubbing surfaces; others may increase tool wear by chemically attacking the tool material.

In some operations the lubricating properties of the cutting fluid may be required for auxiliary rubbing surfaces on the cutting tool. It may be so important to keep these surfaces lubricated that an accelerated wear on the cutting edges due to an E.P. lubricant is permissible.

The reduction in the cutting forces produced by an effective lubricant may be important practically when cutting tools are mechanically weak, *e.g.* screw taps, small drills, and broaching cutters. A reduction in cutting force may also be important in permitting a faster production rate on machine tools where there is a definite design limitation on torque or horsepower. The actual saving in energy consumed by using a lubricant is, however, negligible on account of the relatively small cost of power.

The use of an effective lubricant for reducing the chip–tool friction coefficient has two other important effects. It reduces the tendency for discontinuous chips to form, and also, when the chip is a continuous one, reduces the tendency for a built-up edge to form. In both events the surface finish can be much improved.

PRACTICAL EFFECTS OF THE COOLING PROPERTIES OF A CUTTING FLUID

The cooling ability of a cutting fluid is important in reducing the temperature of the cutting tool and workpiece. Without a coolant the temperature of the tool may become sufficiently high for it to fail mechanically as a result of softening.

In considering the effect of a coolant on the chip surface temperature, it is possible that at low cutting speeds a coolant flowing over the back of the chip may increase the rate of flow of heat across the chip, and hence reduce the temperatures attained at the rubbing surface of the chip. At higher speeds, since the rate of heat flowing across the chip is low in comparison with the velocity of the chip itself, a coolant probably has little effect in reducing the temperatures along the rubbing surface of the chip. It also seems probable that the cooling ability of a fluid, by itself, has no effect on the cutting forces.

CUTTING TESTS CONCERNED PRIMARILY WITH LUBRICATING ABILITY

Cutting Ratio Method

Merchant[6] has shown that, experimentally, the

friction coefficient at the chip–tool interface and the chip–thickness ratio (undeformed chip thickness per chip thickness) were related, and this led to some interest in chip–thickness ratio, as determined for cutting tests in the presence of the cutting fluid, as a means for evaluating cutting fluids.

The experimental relation referred to, however, is different for different metals, and big changes in the friction coefficient cause relatively small changes in chip–thickness ratio. Tests have shown that even with great care, it is difficult to determine the chip–thickness ratio with sufficient accuracy.

Chip–Tool Friction Method

The friction angle at the chip–tool interface in an orthogonal cutting operation is given by [1] $(\tau - \alpha) = \tan^{-1} F_t/F_c$, where α is the rake angle, F_t and F_c are two components of the resultant cutting force. (Friction at the flank face of the tool is neglected.) (Fig 1.) Thus a measure of the lubricating effect of cutting fluids may be obtained in a simple cutting test in which the resultant cutting force is measured. However, the friction coefficient so obtained is dependent upon the rake angle used. Relative ratings can be obtained by standardizing the rake angle used. Shaw [7] has proposed this method for evaluating extreme pressure lubricants in general, since it eliminates the need for preparing the very clean surfaces required in some other types of friction tests.

Critical Rake Angle Method

A method for assessing cutting fluids based on the change in chip formation and finish caused by a lubricant has been suggested,[8] and is claimed to give satisfactory agreement with independent field ratings. Shavings are cut orthogonally, using the cutting fluid under investigation, at a number of rake angles. The rake angle at which the transition from a continuous to a discontinuous chip occurs, is termed the critical rake angle, and is used as the criterion of evaluation. When a number of cutting fluids were tested, the range of critical rake angle was 5° to 20°, compared with 26° for dry cutting.

The magnitude and direction of the resultant cutting force at the critical rake angle were found to be constant for different cutting fluids. The method, therefore, appears to evaluate the chip–tool friction coefficient for the various cutting fluids.

Depth of Plastic Distortion Method

The severity of the plastic deformation in the material below a machined surface is altered by the use of an effective cutting lubricant. This is the basis of another proposal [9] for evaluating cutting oils. The depth of the plastic deformation below the cut surface is determined by taking a series of back-reflection X-ray diffraction photographs, and successively etching away material from the surface.

The greatest variation in the effect of different oils was found at low cutting speeds; at 70 f.p.m. no difference in the oils could be observed, though the difference between the use of oils and dry cutting could be detected at that speed.

This test appears to evaluate the friction-reducing ability in the more direct test mentioned earlier in this paper.

EVALUATION METHODS INVOLVING TOOL WEAR

General

The validity of accelerated tool wear tests for evaluating the effect of cutting fluids on tool life is particularly doubtful because the effect of cutting speed on the behaviour of cutting fluids is so great. However, tests carried out at normal speeds are lengthy and use up large amounts of test material; this is troublesome because, even with great care, it is difficult to obtain test material having uniform machinability.

Radio-active Tracer Techniques for Measuring Tool Wear

Radio-active tracer techniques have been applied to the study of cutting tool wear at the Royal Institute of Technology at Stockholm [10] and at the Cincinnati Milling Machine Company.[11]

In the latter work the cutting tool is made radio-active by irradiating it with neutrons. The material

FIG 3

TYPICAL FLANK WEAR CURVE

worn from the surface of the tool is transferred to the surfaces of the chip and the cut surface, or is lost as dust in the cutting fluid. Experiments show that the amount of material lost in the cutting fluid is small, and certainly less than 10 per cent of the total. By counting the gamma radio-activity of a known weight of chips, a measure of the material worn from both faces of the tool is obtained. Conveniently, many cutting tool materials contain cobalt which, after irradiation, yields Co_{60}.

The tool tips each have four cutting edges and weigh about 2 g; their activity is about 40 millicuries each. To conduct the wear tests on the linear portion of the initial wear curve (Fig 3), a small flat is ground on the flank face of the tool about 0·003 inch deep before the tests are started in order to simulate wear.

In comparing two cutting fluids, cutting tests, each lasting about 10 sec, are carried out alternately, first with one fluid, then with the other. The repeatability of the results is ± 5 to ± 10 per cent for 95 per cent confidence limits. The repeatability of conventional

tests, using flank wear as the criterion, is believed to be about ±35 per cent for the same confidence limits.

In a recent series of tests [12] on the effect of one ingredient, at three levels, on the behaviour of a cutting fluid, a total of eighteen tests was carried out using the radio-active technique. The total time required was 8½ hr and the work material used weighed 2 lb. It was estimated that the same tests carried out by conventional tool-life testing techniques to the same degree of accuracy would have taken six weeks and consumed 1·5 tons of work material.

Care and proper design of the experimental apparatus and the necessary shielding have resulted in the actual dose of radiation received by any individual engaged in this work being many times smaller than the permitted safe dose.

Preliminary work on the development of a radio-active tracer technique for evaluating, under dry conditions, the machinability of resulphurized and leaded free-cutting steels has been carried out by Boulger [13] at the Battelle Memorial Institute. Cutting tests were carried out alternately on different metals, and an inheritance effect was observed—the effect of cutting one metal was observed in the following test on another metal. The reason for this phenomenon is unknown at the time of writing.

Tool Life Turning Tests

Standard procedures have been laid down for carrying out life tests on cutting tools.[14] These are applicable to the evaluation of cutting fluids. It has recently been suggested [15] that a lathe test for the evaluation of cutting fluids gives good correlation with field-performance tests over widely varying conditions and for different types of cutting fluids, ranging from a mineral oil with extreme pressure additives to the straight, water-soluble oil.

The test is, however, an accelerated test, the range of cutting speeds used for the high speed steel tools being 90 to 160 f.p.m. The test procedure enables the results to be corrected empirically for differences in the machinability of the test material.

ASTM Turning Test

In this test a measure of the tool wear is obtained by expressing the increase in diameter of the work-piece in a turning operation as a proportion of the distance cut by the tool. Committee D2 of the American Society for Testing Materials has, over the past few years, been organizing co-operative test programmes in industry in order to assess the practical value of this turning test and the flank wear test described in the next section.

A number of laboratories participated in two series of tests on a number of different cutting fluids. Considerable care was used in obtaining uniform test material; the high speed steel cutting tools were made from the same billet of high speed steel, and ground under the same conditions. The results showed that there was fair agreement that one of the fluids—a conventional water-soluble oil—gave the least wear. Statistical analysis showed that a major portion of the variations in the results was attributable to the test method itself. It was concluded that the reliability of the tests was too weak to enable anything but the difference between the performance of major groups of oils to be assessed; it was not possible to distinguish between finer differences in oils. The inability to discriminate between the cutting fluids was no doubt due to the relatively high cutting speed of 200 f.p.m. used in these tests; at this speed the effects of extreme pressure additives are likely to be small.

Flank Wear Tests

The evaluation of cutting fluids by measuring their effect on the growth of tool flank wear has been used extensively. The depth of flank wear is measured with a low-power microscope at intervals during the life of the tool (Fig 3).

This test method has also been studied by the ASTM. In these tests, conducted with steel tools at a cutting speed of 60 f.p.m., care was again taken to ensure as great a uniformity as possible in the test and tool materials, in tool grinding, and in the test procedure; independent checks were made of the wear measurements. The different laboratories, however, while getting consistent results themselves, did not agree with each other; some found that dry cutting gave less wear than when using a cutting oil, and some found the reverse; others found no difference. Further efforts are being made to increase the reproducibility of these tests.

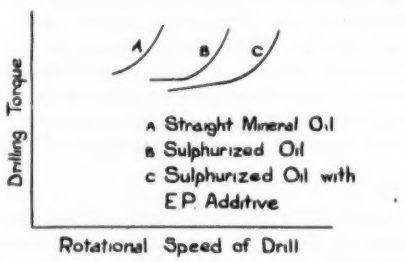

FIG 4

TYPE OF RESULT OBTAINED FROM THE DRILL TEST

Drilling Test

A drilling test [16] for the evaluation of cutting fluids which is claimed to give good correlation with performances in the field in a wide variety of machining operations consists of drilling a series of holes in the presence of the oil being evaluated and measuring the drilling torque. The feed per revolution is kept constant, but the rotational speed of the drill is increased progressively for each consecutive hole. The torque rises as the drill wears until failure occurs; thus, if a cutting fluid manages to reduce the tool wear, the torque curve remains lower than with less effective cutting fluids (Fig 4). It has been pointed

out,[17] however, that there are two important effects which occur in drilling which are not characteristic of other types of machining operations. The first is the importance of getting a coolant to the cutting edges at the bottom of the hole; the application of a coolant through a central hole down the axis of the drill can have a large effect on tool life. The other effect occurs in drilling fairly deep holes. Here the lubrication of the flutes of the drill against the walls of the hole may be most important; drill life may be increased by using an extreme pressure lubricant, even though this actually increases the wear on the cutting edges of the drill.

DETERMINATION OF ACTIVE SULPHUR AND CHLORINE

The determination of the active sulphur and chlorine in cutting fluids is a routine procedure in a number of laboratories, since it is the active parts of these constituents which influence the behaviour of the cutting fluid. Certain mineral oils may contain as much as 4·0 per cent sulphur, though the active sulphur may be zero; such an oil exhibits no extreme pressure properties.

In essence, the various methods [18,19,20] used consist of determining the amount of sulphur in a sample of cutting fluid which reacts with a known weight of metallic copper. (Tests have been done with iron, cadmium, and silver, but copper is most widely used.) The copper is used in the form of powder, turnings, or gauze, and reduced to make its surface chemically reactive. The test is carried out at different temperatures according to the procedure adopted. Some laboratories carry out the test at a number of different temperatures, since the proportion of chemically active sulphur and chlorine depends upon the temperature at which the test is carried out; cutting fluids may exhibit different relative activities at different temperatures. Tests of this type are not applicable to cutting fluids containing fatty material, since sulphur reacts with the fat instead of with the copper.

EXTREME PRESSURE LUBRICANT TESTERS

Extreme pressure lubricant testers are used widely for the preliminary screening of cutting fluids. The basic elements of some of the machines used for this purpose are shown in Fig 5.

Typical results obtained with the Falex machine are shown in Fig 6. It is results of this type which have probably given rise to a special terminology used in connexion with extreme pressure additives. The materials (such as sulphurized oils) which cause the friction torque to rise with increasing load (curve A) are termed " anti-weld " agents; with these materials, though the friction torque rises, the load-bearing capacity of the surface film is high. Curve B is typical of results obtained with the so-called " lubricity " agents; the friction torque remains low, and the load-bearing capacity of the surface film is high. Typical lubricity agents are the chlorinated oils and the fatty materials such as lard oil. The

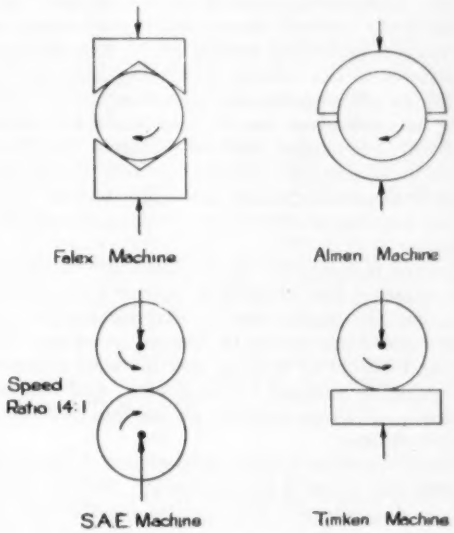

Fig 5

PRINCIPLES OF E.P. TESTING MACHINES

reason for the difference in the behaviour of these materials in this machine is a matter for conjecture; both types of substances can be shown to reduce the chip-friction coefficient in the cutting test mentioned earlier.

The ASTM is conducting a co-operative test

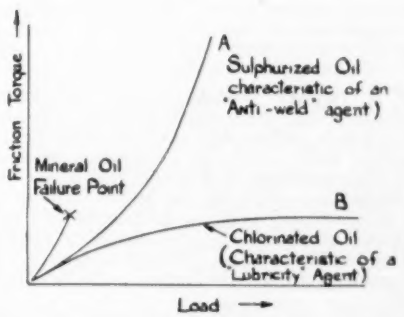

Fig 6

TYPICAL RESULTS OBTAINED WITH A FALEX MACHINE

programme on the use of the Falex and Timken machines for predicting the performances of cutting fluids. Preliminary work has been concerned with determining whether results obtained by different laboratories agree; later work will attempt to correlate the results with tool wear tests.

CONCLUSIONS

An attempt has been made to discuss the effect of lubricating and cooling properties on the performance of cutting fluids, but few definite conclusions can be drawn. Lubricating properties, and these are effective at the lower end of the cutting speed range, are important in improving surface quality and decreasing the stresses in the cutting tool; they may improve tool life by altering the cutting temperatures and by acting as anti-wear agents between the surfaces; but there is a danger that the chemical activity of certain lubricants may increase the rate of tool wear. Probably the cooling properties of fluids affect cutting tool life because of their effect on the temperature of the tool.

Extreme pressure testing machines are widely used for evaluating the lubricating properties of cutting fluids, but the cutting test for determining the chip-friction coefficient seems to deserve more use. The combined effects of cooling and lubrication on tool wear must be assessed by wear tests, and the most promising of these appears to be the radio-active tracer technique.

The co-operative testing programmes of the ASTM suggests that some of the evaluation tests at present used in laboratories give results insufficiently reproducible to be valid, particularly when finer distinctions are required than just between the major types of cutting fluids.

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The experimental results given in Fig 2 are published by permission of the Director of the Mechanical Engineering Research Laboratory of the Department of Scientific and Industrial Research. The author wishes to thank W. S. McDougall of the same laboratory, who helped to obtain these results. He also wishes to thank all those in the U.S.A. who have given time to discuss this subject, and the American Society for Testing Materials for permission to mention the results of its co-operative test programmes.

The author is indebted to H. A. Erickson of the D. A. Stuart Oil Co., Chicago, Illinois, for permission to quote unpublished data in Fig 6.

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DISCUSSION

Dr C. B. Davies: Performance in metal-working is assessed on the basis of criteria such as rate of production, rate of tool wear, and quality of the product. A study of performance with a view to progressive improvement involves the consideration of factors such as the material of the work piece and tool, the design of tool, its conditions of operation, and the properties and mode of application of the fluids which are almost invariably used to facilitate metal-working. This symposium is intended to deal mainly with the role played by the fluid in metal-working.

Dr Galloway, the director of research of the Production Engineering Research Association, and Professor Thompson, Professor of Metallurgy in the University of Manchester, have kindly agreed to share the task of initiating discussion by summarizing the outstanding features of the papers. The objective of this meeting is to stimulate a lively discussion on the subject of metal-working. This afternoon Dr Galloway will deal with the papers on metal cutting, and in the case of the first paper on the programme, "The Mechanism of Friction and Lubrication in Metal Working," by Drs Bowden and Tabor, Dr Galloway will refer only to those portions of the paper concerned with cutting. Professor Thompson will deal with the remainder of Dr Bowden's and Dr Tabor's paper in opening the session this evening.

Following Dr Galloway's review, you will be invited to contribute to discussion of the subject of Metal Cutting. A similar pattern will be followed this evening, starting with Professor Thompson's review. Now I have much pleasure in calling on Dr Galloway to guide our thoughts this afternoon.

Dr D. F. Galloway: As it is essential to leave ample time for discussion, I shall restrict my remarks to some of the principal topics discussed by the authors, although this inevitably means that I shall have to pass over a considerable amount of valuable material contained in the papers.

Drs Bowden and Tabor have dealt with the mechanism of friction and lubrication in metal-working operations. Certain fundamentals of the mechanism of friction and lubrication are common to forming and machining processes, but this afternoon we are concerned with metal cutting only. A diagrammatic record of some experiments which demonstrate the importance of the oxide

film on friction between two metals in contact is given in Figs 7 and 8. In these experiments the film which is normally present on a metal surface was removed by heating strongly in a high vacuum. It was then almost impossible to slide the surfaces over one another, and gross seizure occurred even at room temperatures. When the surfaces were pulled apart, extremely heavy damage occurred. When a small amount of oxygen or water was admitted to the surfaces, an oxide or hydroxide film was formed. This procedure greatly reduces surface damage and friction, provided the film is not penetrated.

The authors also show that a lubricant in the solid state provides the best protection for metallic surfaces. There is a marked increase in friction and damage to the surfaces at the melting point of the lubricant, and at higher temperatures further deterioration occurs. In general, fatty acids react with the surface to form metallic soaps, and these have an appreciably higher melting point than the parent fatty acids.

The next section of the paper refers to some experiments with diamonds. Research results given by the authors suggest that adsorbed surface films play an important part in the friction and adhesion of diamonds. Another suggestion is that plastic deformation of diamond surfaces occurs when they rub on one another, although it is generally assumed that the local deformation is elastic. The friction of diamond on diamond is also shown to vary with the crystallographic face and direction. These observations show that despite the excellent frictional and wear properties of diamond, there are many complicating factors that have an important bearing on its performance in metal-cutting operations, and extensive research may therefore be necessary to evaluate the effects of the different factors.

In some experiments which I carried out several years ago, I found that crystallographic face and direction were very important, not only because of possible friction variations, but also because of variations in the resistance of the diamond to chipping, which commonly occurs with industrial diamond cutting tools. The frictional aspect is very important while the diamond is functioning, but from studies in industry, I found that many more diamond tools fail as a result of an accident than of wear, so that this resistance to chipping or fracture is quite important.

Drs Bowden and Tabor refer to the use of additives such as sulphur and chlorine, and point out that some extreme pressure additives may increase tool wear by chemically attacking the tool material. They show that although gaseous cutting fluids have inferior cooling properites, gases may effect a marked reduction in friction in metal cutting. Observations were made when machining aluminium with steel and molybdenum tools in air, and also in an atmosphere of hydrogen sulphide. Although the results obtained are not superior to those achieved with good commercial cutting fluids, they indicate that further experimentation would be justified. The improvement in surface finish shown in Fig 13 was not particularly significant with the steel tool, but pick-up was much less, both with hydrogen sulphide and the commercial cutting fluid. Fig 14 shows, however, that there was a considerable improvement in surface finish when hydrogen sulphide was used.

The paper by Mr Wolfe, Mr Kinman, and Mr Lennard, is a report on preliminary tests of the effectiveness of various chlorinated hydrocarbon compounds as cutting oil additives. Their tests suggest that substituted methanes were more effective when the number of chlorine atoms in the molecule was increased, whereas the effectiveness of substituted ethylenes apparently decreased with an increasing number of chlorine atoms in the molecule. The authors also report indications that maximum effectiveness occurred with a relatively low concentration of additive, although the optimum concentration varied with the different additives. Table IV shows that several of the compounds tested gave longer drill life than carbon tetrachloride. In considering this result it is desirable to bear in mind the test conditions, particularly the cutting speed. According to Shaw, carbon tetrachloride is most effective at cutting speeds below 40 f.p.m., and it is therefore interesting to note that in the investigation made by Mr Wolfe and his colleagues, the speed at the periphery of the drill was 109 f.p.m. The differences in performance are partly dependent on cutting speed, and thus the two conclusions are not contradictory.

The authors point out that the compounds used in the investigation are toxic, and were used mainly to try to establish a relationship between molecular structure and the effectiveness of the compounds as cutting fluid additives. They also stress the need for caution in applying the results of tests that do not exactly simulate working conditions.

An interesting example of the effect of small variations in machining conditions on the results obtained is given in Appendix II of the paper. Very scattered results were obtained in initial drill life tests, because of variations in the oil temperature, which increased from a room temperature of 21° C to between 27° and 29° C during the tests. When the oil was preheated to 27° C before drilling, repeatability was improved, although some scatter remained until the oil temperature was more closely controlled, and the chlorine was added on a weight base.

Mr Stabler has reviewed some of the practical and theoretical phenomena associated with the mechanics of metal cutting. He refers to Merchant's shear theory and points out that a chip is formed by a process of shear, or plastic flow. If the shear occurs uniformly over a flat plane extending between the cutting edge and outer surface of the approaching work, a continuous chip flows over the face of the tool. This condition is most nearly approached when cutting ductile materials under good conditions of high speed. Very high pressures are developed between the chip and tool, and as the chip slides over the face of the tool it encounters heavy frictional resistance. One of the main problems is to reduce friction at the chip–tool interface under these conditions of high pressure and temperature. If a small portion of material adjacent to the cutting edge becomes attached to the tool face, a "built-up" edge is formed. The built-up edge normally breaks down and builds up again very rapidly, it grows until it becomes unstable and is carried away in whole or in part by the chips and the work piece, then re-forms, and continues to build up until it reaches once more a condition of instability.

When the friction between chip and tool face become very high, or if the work-piece material is brittle, a continuous chip may not be produced, and the material may actually rupture intermittently at the shear plane. This results in the discontinuous type of chip produced when machining such materials as cast iron. These segmental and discontinuous chips are shown in Figs 5 and 6, and it will be noted that in Fig 6 there is some indication of the distortion which takes place before rupture occurs.

Mr Stabler refers to the observations of F. W. Taylor and others concerning cracks running ahead of the tool. Such cracks might be of considerable importance in considering the action of cutting fluids, but the author has very correctly pointed out that there is evidence to show that such cracks cannot exist for more than a very small proportion of the cutting time. He also refers to Merchant's observation that non-uniform stress distribution on the chip–tool interface causes a curved shear plane, and therefore curvature of the chip. He mentions various mechanical causes of curvature, including the variation in cutting speed along the lips of a drill, curved rake faces, the shape of chip clearance spaces, and the presence of a chip breaker.

The author points out that the mechanical energy

necessary for metal cutting is converted almost entirely into heat energy at the shear plane and at the chip–tool interface. The temperature reached by the tool may have a marked effect on its life, as the rate of wear generally increases at high temperatures, and thus the thermal properties of the fluid may have an important effect on tool life. Mr Stabler describes an approximate method of calculating the theoretical maximum temperature in machining operations when the density and specific heat of the material are known. The method requires the important initial assumption that all the power appears as heat in the chip alone.

Mr Stabler finally refers to the improvement in surface finish which occurs in intermittent cutting operations for a short distance after the initial entry of the tool into the work. It is suggested that this is caused by the absence of a built-up edge due to reduced friction resulting from contamination of the tool when it is not cutting. The non-cutting period also permits the dissipation of heat from the tool, and the removal of chips from the tool surface by the cutting fluid may further reduce the temperature.

The paper by Mr Morton and Mr Tourret deals with the mechanical testing of cutting fluids. The authors have sub-divided methods of assessing cutting fluids into three groups as follows :

(1) workshop trials ;
(2) machining tests under laboratory conditions ;
(3) simulation or bench-type laboratory tests.

They consider that the results of workshop tests are often influenced by prejudice and the effect of such secondary characteristics as appearance and smell. Some successful field tapping tests have been carried out in the Netherlands, but unusually strict control was maintained over material specification, tool material, tool preparation, and operating procedure. The general conditions were thus similar to those which are established in laboratory investigations.

Because of the difficulties of conducting satisfactory field trials, the authors' company has sponsored various machining investigations at PERA. For example, drill life tests have been used as a basis for assessing the effectiveness of straight cutting oils. These tests revealed clearly the influence of various additives, and indicated the relative merits of different fluids. Straight mineral oils had a comparatively poor performance, but their effectiveness was improved by additions of sulphur or sulphurized fat, or of a chlorinated hydrocarbon.

Considerable differences were observed in the performance of oils of similar composition blended with alternative sulphurized bases. Fatty acids had a beneficial effect on performance, and this result confirms the remarks made by Drs Bowden and Tabor on fatty acids. Rapeseed oil is popularly supposed to give excellent performance, but in tests carried out by PERA, an oil containing rapeseed oil was greatly inferior to the best oil tested, even though an unusually smooth cutting action occurred with the rapeseed oil. Torque and thrust were very consistent, and there was also little smoke or smell. More recent drilling tests have been useful in discriminating between different soluble oils.

Investigations into turning and tapping have also been undertaken for the authors' Company by PERA, and tests of this type are being continued. It appears that single-point tool life tests using straight cutting oils are in good agreement with previous drill life tests. Some interesting results indicate that work-piece surface finish deteriorates as tool life increases.

Tests on a smaller scale are being devised at the Thornton Research Centre. These tests, although less precise than the PERA investigations, are considered by the authors to be satisfactory for making a preliminary selection of potential cutting fluids. A small drilling machine which is being used in the investigation has been fitted with a constant-weight feed for standardized drill life tests.

Metal-cutting investigators have often assumed that short tests in which cutting forces were measured would give an indication of tool life. They argue that it is reasonable to suppose that cutting forces will bear some relation to tool life, tool life being greatest when cutting forces are at a minimum. Mr Morton and Mr Tourret have now confirmed previous research results, obtained by Mr Morton and myself, which show that there is no useful relation between drill life and the initial torque and thrust on the drill. The authors conclude, however, that metal-cutting investigations in which dynamometers are used should lead to a better understanding of the processes involved, and should therefore indicate the lines along which cutting fluids might be improved. They consider that the work undertaken in the past few years has undoubtedly increased understanding of cutting fluid requirements, and has shown that there is no substitute for practical tool life and surface finish investigations when selecting cutting fluids for commercial purposes. They show that laboratory inspection tests that do not involve actual metal-cutting operations have not been satisfactory. For example, a four-ball testing apparatus for extreme pressure lubricants has not revealed important differences in the cutting performance of different sulphurized oils.

Mr Grisbrook has given a very short account of some of the problems of assessing the effectiveness of cutting fluids in the factory. He has also referred briefly to some of the factors involved in the selection and use of cutting fluids. Several references are made to laboratory tests of cutting fluids, and it is important to bear in mind that under ordinary conditions factory tests have a very limited application. This has been emphasized by Mr Morton and Mr Tourret on the basis of their experience in British industry. Investigations carried out on the production site can produce very misleading results unless trained research personnel supervise the tests, and ensure effective observation and control of the various factors and criteria involved. There is a common illusion that these so-called field tests carried out on the production site are much cheaper than properly controlled practical tests carried out under laboratory conditions. The reason for this is that the costs involved are usually hidden or absorbed in the cost of the production department as a whole.

Mr Chisholm's paper is a digest of U.S. practice in relation to cutting fluid assessment. He emphasizes the difficulty of getting fluid to those parts of the cutting zone where it can act as a lubricant, referring particularly to the work of Lauterbach, and the practical application of these principles by Piggott and Colwell in the Hi-jet system of cutting fluid application. The speed aspects of these difficulties are illustrated in Fig 2, which shows that the cutting fluid was very effective in reducing specific cutting pressure at low speeds, but as speed increased the wet and dry curves approached each other, giving a common value of specific cutting pressure which indicates that the effect of the cutting fluid on cutting pressure was negligible at about 450 f.p.m. At a cutting speed of 200 f.p.m., however, the application of cutting fluid reduced the cutting pressure to less than half the value when cutting dry. The paper contains a brief reference to the cooling effects of cutting fluids, and also refers to the various proposals for evaluating cutting fluids, including the use of Merchant's cutting ratio, chip–tool friction, critical rake angle, and depth of plastic distortion. The author refers at greater length to various types of tool wear test such as that based on the use of radioactive tracers, and concludes with reference to lubricant testing.

I feel the Institute of Petroleum is to be complimented on arranging the symposium on metal-working at such an opportune time. There is a considerable concentra-

tion of attention on such organizational aids to higher production as work study, time and motion study, etc., all of which play a part in increasing productivity, but even among engineers, there is not enough appreciation of the great potentialities which exist for improving individual techniques in metal cutting and metal forming by dealing with the purely engineering problems in these operations. I am referring not only to such highly publicized developments as the use of carbon dioxide as a cutting fluid, the Hi-jet process, hot machining, high-speed hobbing, etc., but to the improvement of techniques in conventional metal-cutting and metal-forming operations. In the past few years considerable economic gains have been made by production plants applying improved metal-working techniques, and I am sure that the information made available at this symposium will also have far-reaching results if it is properly applied in industry.

Dr F. T. Barwell: The organizers of the symposium are to be congratulated in selecting as the first paper so fundamental a study as that by Drs Bowden and Tabor. Standing out in that paper is the elegant reflection technique of electron microscopy. This constitutes an excellent means for studying in great detail the reaction of tool on work and tool on chip. Although Fig 3 is a case in point, I think engineers would say that it represents scratching rather than cutting. A similar study of a true cutting action producing a chip might be very revealing, and it is hoped that Dr Tabor and his colleagues will be encouraged to extend their work in this direction. The paper mentions several techniques for observing surface damage, and I would like to stress the importance of combining different methods of observation in the studies of actual processes. For example, due to the high magnification employed, the electron microscope can examine only a very small portion of a surface at any one time. If we have available techniques suitable for examination of a wider area, we are able to ensure that the limited area selected for detailed study is representative of the whole area under examination. One such method is the "Linik" interference microscope. Fig A (*a*) and (*b*) shows two surfaces of polished aluminium as seen through a Zeiss "Opton" microscope—that on the left shows a mechanically lapped specimen; the other, on the right, an electrolytically polished specimen. Under visual examination the electrolytically polished surface appeared to have a very much smoother surface. However, the interference fringes show clearly that the lapped surface is in fact the flatter of the two.

The method is of considerable value in so far as the lines can be regarded as contours, which enables one to study quantitatively the deformation of a surface. Fig B (*a*) and (*b*) show how that can be done. Here a hemispherically ended hard steel slider ($\frac{1}{4}$ cm radius) has been passed across surfaces of soft aluminium and lubricated with oleic acid under a load of 200 g. If the lines are regarded as contours it is easy to see how it is possible to study the whole depth of the scratch. It is also interesting to note the difference between the type of damage occurring on the lapped specimen, and that suffered by the electrolytically polished specimen.

Considering the symposium as a whole, it is surprising that it reveals little effort of a research character to bridge the gap between Dr Tabor's fundamental work and what happens in the machine tool itself. The careful experiments of Wolfe and his collaborators, using different additives, supply valuable evidence for correlating the chemical nature of the cutting oil with the life of drills. However, as mentioned above, the special character of the drilling test does not provide sufficient basis for generalizations about cutting oils. On p. 264, Morton and Tourret remark that oil 13 gave unusually smooth cutting, consistent torque, and thrust. However, they rate it below the best on a basis of drill life. Is this fair? It is true the authors may be more concerned with roughing operations than with finish, but as Mr Grisbrook infers in his paper there is strong objection to having a multiplicity of cutting oils in one shop, and it might be worth while to employ oil 13 in order to achieve smoothness and consistency in finishing operations, with consequent improvement in finish and form of the product, while tolerating some reduction in tool life in a roughing operation.

Mr Chisholm's paper reveals a very disturbing state of affairs from the point of view of the practical evaluation of the merits of cutting fluids. He refers to the unfortunate experience of the collaborators in an ASTM series of tests. A conclusion which might be drawn from his remarks (and this is well supported by his own work as illustrated in Fig B) is that at high speeds of cutting, chemical action is not an important factor in the behaviour of a cutting fluid. The results of drilling tests, whilst no doubt invaluable as a means for selecting the correct cutting fluid for drilling operations and perhaps other slow speed operations, may be quite meaningless in relation to a high speed operation. This points clearly towards the need for research into the fundamentals of the cutting process and the need for the basic approach so well illustrated in the first paper. It should be emphasized that this need is not being met by the use of extreme pressure lubricant testers. In Fig 5 in Mr Chisholm's paper we have the SAE, the Falex, the Almen, and so forth. These machines were developed for a fundamentally different purpose, *i.e.* for testing gear oils. Whilst I do not wish to give my opinions this afternoon on their merits or demerits for their original purpose, it is clear they cannot represent the situation in cutting, where freshly cut, chemically clean metal undergoes the rubbing process, as is the case in all machining operations. Perhaps the best of the EP testers, the Boerlage four-ball machine, is shown by Morton and Tourret not to reveal important differences in cutting performance. There is great risk in the U.S.A. of much hard, well-controlled statistical work being rather wasted because the proper tools for the job have not been developed, and I do not believe we shall alter that until we understand more clearly the physical and chemical processes which operate when metal is cut at high speed.

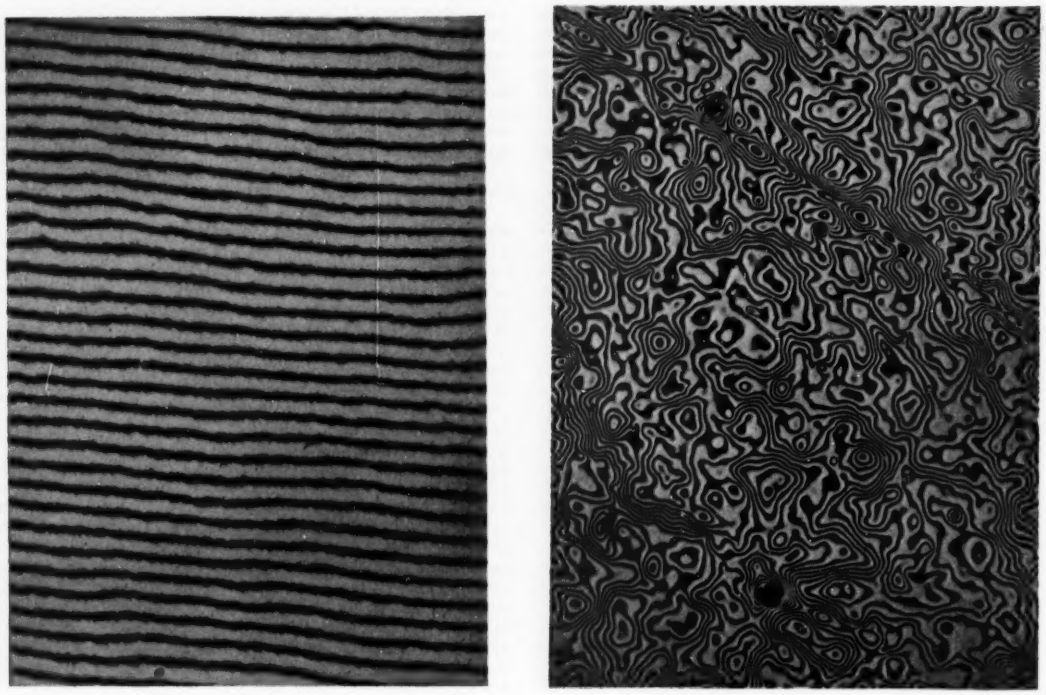
L. Grunberg: Dr Barwell has mentioned the necessity of a more fundamental approach to the study of metal cutting. One of the problems which still requires elucidation is that of the chemical reactions which occur between the cutting fluid and the freshly exposed metal surface. At the Mechanical Engineering Research Laboratory we carried out some experiments in which various metals were cut under water which contained dissolved oxygen.* After a number of cuts had been made the water was analysed and found to contain measurable quantities of hydrogen peroxide. Some of the results obtained are given in the following table:

TABLE A

Metal	Area exposed per cut, cm²	No. of cuts	Cutting speed cm/sec	Mg H_2O_2 formed
Zinc . .	21·3	450	2·12	2·75
Aluminium .	19·6	450	2·12	2·38
Magnesium .	16·9	456	1·92	2·66
Nickel . .	21·6	655	2·80	2·47

Under similar conditions copper gave only traces of H_2O_2, whilst iron gave the equivalent of 5·62 mg H_2O_2

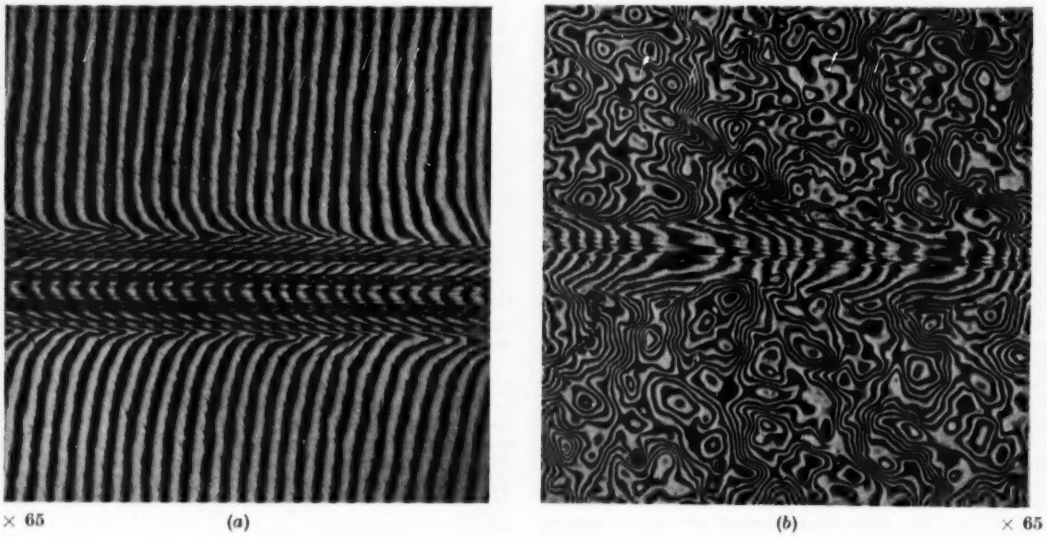
* Grunberg, L. *Proc. phys. Soc. Lond.*, 1953, **66**, 153.



× 65 (*a*) (*b*) × 65

FIG A

INTERFERENCE MICROGRAPHS OF PREPARED SURFACES



× 65 (*a*) (*b*) × 65

FIG B

INTERFERENCE MICROGRAPHS OF FRICTION TRACKS

in the form of ferric ions. The chemical reactions which lead to the formation of H_2O_2 are very complicated, and are initiated through the transfer of electrons from the metal to water molecules. The following reaction scheme is probably applicable :

$$e + H_2O \longrightarrow H + (OH)^-$$
$$H + O_2 \longrightarrow HO_2$$
$$HO_2 + H_2O \longrightarrow H_2O_2 + OH$$
$$e + OH \longrightarrow (OH)^-$$

Those familiar with the chain reactions in combustion or lubricant deterioration will recognize the free radicals HO_2 and OH which are involved in all these processes. The hydroxyl ions $(OH)^-$ lead to the formation of metal hydroxides, the presence of which we were able to prove.

Similar processes occur when metals are cut in the presence of carbon tetrachloride. When cutting aluminium in carbon tetrachloride Shaw * found that the reaction product could be resolved into aluminium chloride and hexachloro-ethane. This can be explained by the following reactions :

$$e + CCl_4 \longrightarrow CCl_3 + Cl^-$$
$$Al^{3+} + 3Cl^- \longrightarrow AlCl_3$$
$$2CCl_3 \longrightarrow C_2Cl_6$$

In this case the free radical CCl_3 is involved.

In the paper by Wolfe, Kinman, and Lennard it is stated that carbon tetrachloride was found to be less effective than hexachloro-ethane. From a chemical point of view there appears to be no reason why the two substances should behave differently, and it is likely that the greater volatility of carbon tetrachloride reduced the effective concentration of this compound at the cutting face, with a corresponding loss in performance. I understand from Dr Galloway that this is only a preliminary paper, and I would encourage the authors to pursue a fundamental study, parallel with the determination of the number of holes drilled, when using a certain type of chemical compound. The identification of the products of the chemical reactions involved may provide a better understanding of the mode of action and a sounder basis of the selection of cutting oil additives.

Dr C. B. Davies : Concerning the subject of activation of a metal by cutting, you are probably all aware that the Cincinnati Milling Company has developed a chemical reactor for making special compounds, such as novel Grignard reagents, which are difficult to obtain normally. They are prepared in the Cincinnati Mechanical Activation apparatus by cutting metal such as magnesium under appropriate reagents and so facilitating direct formation of the compounds desired.

H. L. Bingham : The paper contains quite a lot of data, but I am particularly interested in the surface finish results given in Table VII, p. 267. The authors state that the results relate to a specific series of tests, but I would like to know whether the tool angles and operating conditions were chosen to be representative of industrial practice and whether it is intended that the results can be interpreted as the levels of quality given in the average workshop. The reason I ask is because from my own experience a proper evaluation of surface finish is not an easy task to the laboratory. We have found that surface finish values, measured within the range of the Talysurf, follow a cyclic form with cutting speed, and that no regular phasing is present for many cutting oils used. In the same way, the change in surface finish with length of cut does not follow a regular pattern. As a result of this, we have found it best to evaluate surface finish in terms of an appreciation of results over a range of operating conditions chosen to embrace those used in service.

The other point I would like to discuss very briefly is in connexion with the combined tool life and surface finish tests (pp. 263–265). The authors found that a deterioration in surface finish was given as tool life increased. This can be explained in terms of progressive tool wear. In some fairly recent work Pekelharing and Shurman have described a sequence of tool wear with continuous cutting, and have shown that the work-piece feed marks resulting from the turning operation influence both the rate of wear and the manner in which wear of the cutting edge occurs. Their work relates to cemented carbide tools, but it is not unlikely that a similar form of wear would be given with H.S.S. tools.

Dr D. Clayton : It is very important in considering this subject to get a proper sense of relationship between the practical tool tests and the laboratory tests; as Dr Galloway rightly urges, we should give very great importance to practical tool tests, but they do not tell us in detail about the cutting process and, therefore, something else has to be done. It is quite clear from all these papers that many people have approached the subject from a laboratory point of view, and I would be the last to say that that would be unprofitable, even though, in many cases, the results may not tie up comprehensively with the practical tool tests. I think the secret is to adopt an analytical approach. In regard to the extreme pressure testing machines, it might be asked how they alone could serve to evaluate a cutting fluid—for broadly there is little similarity between the action of those machines and the tool in cutting. But that does not infer that attempts should not be made on similar lines to sort out the problem (in these machines, finding out what happens when one metal slides over another under severe conditions), and it is quite clear from the literature as well as these papers that that attempt is being made, and with some success.

Dr Galloway has mentioned that in the paper by Morton and Tourret the force tests do not accord with tool life tests. That might seem to be a criticism of the analytical approach, but surely the analysis has not gone far enough. Most of the analytical thinking has been done on the basis of the diagram of the tool–chip contact forces, involving the friction force of the chip on the tool. On that basis, there seems no reason why there should not be accord in cutting forces and tool life, but no one yet has dealt adequately with the edge of the tool in relation with the work. There is vague reference throughout these papers to the surface finish being affected by the tool and the cutting conditions. Apart from the effects of the built-up edge, no one has analysed the problem to show what it is in detail that influences surface finish as the tool runs over the work. Clearly we are more concerned with what Mr Chisholm, in Fig 1, on p. 271, refers to as flank wear. What happens in that region affects tool life and finish. I cannot say what detailed mechanism influences the finish, but consideration of it leads to the inference that corrosion might be important. This is not considering the action of the corrosive material as beneficial on the new metal of the chip running over the top face of the tool. What then happens as the other new surface runs past the edge of the tool? Clearly, if there is any attack on the tool edge, it will be worn very quickly, as Mr Chisholm points out, and the life will be reduced. It is still desirable to lower the viciousness of the new surfaces coming into contact with this edge of the tool. The requirement appears, therefore, to be a lubricant with material in it which under the operating conditions is corrosive to the work but not to the tool. In that respect the experiments of Drs Bowden and Tabor (at the end of their paper) are very interesting, but they do need further analysis.

In considering the practical side I had a lot of sympathy

* Shaw, M. C. *J. appl. Mech.*, 1948, **15**, 37.

with Mr Grisbrook's paper. It is really very important indeed to find out what the broad indications are of all this work. For example, do all sulphurized fatty oils added to a mineral oil base improve drilling and tapping? Reference has already been made here to E.P. lubricants. Sellers of cutting fluids refer to E.P. cutting oils quite freely; they mean those tested in the conventional E.P. test machines—it is safe to say that few of them have tested them in a practical way. Most suppliers market a range of oils: ordinary soluble oils, clear soluble oils, E.P. soluble oils, plain mineral oils, compounded oils, E.P. oils, and so on; and they advertise them as suitable for particular cutting operations. It is quite clear that they have not tested all of them in a practical way, in order to show that they do give the result claimed for them in the catalogues, and in the present state of knowledge there is a measure of deceit in the claim of the quality of the material that is being sold. Can anyone say whether all the marketed cutting fluids under a particular generic heading, such as a sulphurized fatty oil, will behave in a reasonably uniform manner in the cutting operations for which they are generally advertised, or will the spread of the materials from different suppliers be so great that they cannot justifiably be categorized? The expenditure in cutting metals is so large that it would be well worth while if some organization, such as Dr Galloway's, could guide users broadly as to the qualities in a few common operations of these different cutting fluids in their various categories.

G. V. Stabler: The caption to Fig 2 of Bowden and Tabor's paper states that "The grooving and minute chatter marks due to intermittent sliding are clearly seen." Now, I question whether that is true. There are certainly marks in the track, but it is clear that they are in exact accordance with the surface marks already on the surface as originally caused by the polishing process. It appears that the conditions shown in Fig 2 do not resemble metal cutting as made by a lathe or milling machine, but are more like the result of a continuous indentation test, giving cold work rather than actual cutting.

The same condition is slightly visible in the right of the groove in Fig 3, where the surface finish marks originally on the surface appear to go partly down the groove. I would be grateful if the authors would describe the shape of the tool which has produced the groove. There is superimposed a diagram which shows it to be a 90° diamond of some sort, but the face which produced the cutting is apparently orthogonal to the groove and has zero rake, and I am puzzled how the two sides of the groove have been formed. The one on the right-hand side of the diagram appears to be very smooth cutting indeed; the other is very irregular, and the material which has been moved appears to be on one side of the groove only.

R. P. Langston: In view of the work being done on drilling tests for cutting oil evaluation, it is thought that the results of certain tests carried out on Ministry of Supply oils might be of interest. During the past two years samples have been examined at B.S.A. by their drill test.

The reason for this work was due to feeling that the buying of cutting fluids to a specification resulted in a cheap fluid that met the technical requirements of the specification, whereas actual performance as a cutting fluid depended to a certain extent on prices. A collection of samples from eighteen different oil firms were available, and these were subjected to the B.S.A. drilling test at the B.S.A. machinability laboratory. Milky soluble cutting oils which were intended to meet the specification CS. 1662C were the only ones considered.

The drilling test used at B.S.A. is well known, but the details are included for completeness. The cutting oils were used, diluted 20 : 1, as a coolant for drilling holes $\frac{1}{4}$ inch diameter, with jobbers' drills of tested performances, in tyre billets (BS328), under the following conditions:

Spindle speed 3340 r.p.m.
Depth of hole $\frac{13}{16}$ inch
Drilling time 3 sec
Rate of penetration 16 inch/min

Oils were supplied under code letters to B.S.A., and each result was the average of three determinations. We realise that the oils have been tested at a 20 : 1 dilution, which for some of them might not be the dilution at which they give their best performance, and also that a drilling operation is not the same as a cutting operation. However, we think it is significant that in a standard repeatable test in which metal is being removed in the presence of the coolant, values ranging from 116 to 486 were obtained. This means that drills lasted consistently four times as long with some cutting oils as with others for this particular metal removing operation.

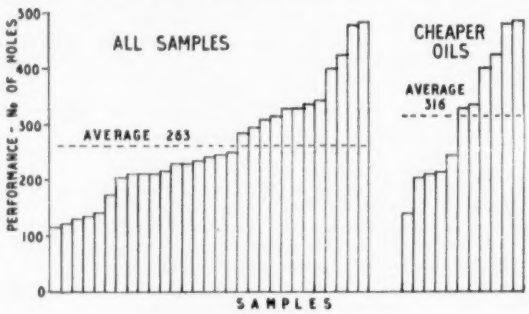


FIG C

Samples of oil were tested so that we could have a background of results on which to base further work, and these results are shown in Fig C. The average value of the performance of these oils is 263.

Some of the oils were too expensive to be considered for use, but for those which were economically permissible an average performance of 316 holes was obtained. It would seem that performance and price are not necessarily related.

TABLE B

Firm	Results of tests	Firm	Results of tests
A	135 402	J	294
B	121 232	K	486 139 215
C	232 245	L	236 330
D	309	M	482 286
E	313	N	250
F	211 347	O	244 208 330
G	176	P	130
H	207 337	Q	116
I	205	R	428

The performance of the various oils listed against the suppliers is shown in Table B, and it is noticeable that results of performance tests on different samples from any one firm may differ widely. It therefore appears that some cutting fluids are not controlled by performance tests when blending is being carried out.

For many cutting operations oils with the lowest ratings would be adequate, but it may well be that for the more exacting operations and operator may have to change from a normal soluble cutting fluid to a neat cutting oil or an E.P. soluble oil because of the poor quality of his normal supplies.

Our experience confirms the necessity for a cutting performance test for cutting fluids, and the one used at B.S.A. appears suitable.

If the level of results quoted in Table IV, p. 266, are used as a guide, it would seem that we are being offered oils which in performance range from tap water to E.P. soluble oils.

These results are published by permission of the Chief Scientist, Ministry of Supply.

A. L. H. Perry: I just want to say a word on behalf of the oil suppliers in relation to one or two of the comments made by Mr Langston, and in regard to his variable figures. We can say with a fair degree of certainty that the fault is in Mr Langston's tests, and in saying this I am not criticizing those tests, but referring rather to the difficulty of testing. We find the same thing in our own laboratories. Using every refinement of control, we still get very wide variations in tool lives—that is one of the problems of tests on metal cutting. In the case of soluble oil emulsions, it must be realized that they are complex systems, liable to fortuitous variations which are not always perfectly controllable, but even when they are as well controlled as is possible, these variations still occur. This emphasizes the difficulties of such work, and, perhaps, the need for new techniques.

As in the laboratory, so in the field. I recently encountered a case in Sweden, where a customer had made a lot of field tests on the turning of crankshafts, using a wide range of soluble oils. We supplied a variety of these, ranging from a conventional opaque soluble oil to an E.P. soluble oil that was heavily loaded with E.P. additive. (In certain operations this E.P. soluble oil is known to give much higher tool lives than the opaque soluble oil.) Now, in his tests this customer found variations in tool life, with the same oil, of about 14 : 1, although for tests under production conditions his work was of a very high standard. Another interesting point was that, when all the results were averaged out, there was very little difference between any of the oils. We thought that in view of the bad repeatability, the observed differences were statistically not significant, though the customer did not entirely agree on this point. However, assuming that our view was correct, it confirms some tests of our own, where we found that in a certain plain turning operation there was no significant variation in tool life with widely different soluble oils. This is one of the great difficulties with this type of work—every operation is different; and whereas in one type of machining there are differences between particular oils, in another type there is no difference, according to whether the thing is controlled by cooling or by friction, and so on. This is why it is possible to state almost definitively that there is no possibility of having a universal cutting oil test.

Professor H. Ford: We should be rather careful in talking about coefficients of friction in relation to a metal-working process. In particular, I would like to refer to one statement made by Mr Stabler, in which he says that the pressures were of the order of 100 tons/sq. in., and the coefficients of friction were of the order of unity. If that were so, it would mean that there was a tangential stress on the face of the tool of 100 tons/sq. in., and the material would need to possess a yield stress of that value, if these conditions were to be realized. It is most unlikely to have so high a value, and by the connexion between shear and direct stresses at yield, the material would have yielded by shearing tangentially to the tool face. In other words, the shear component can give rise to a coefficient of friction which is limited to one-half and no higher. The shear lines would run parallel to the surface, and that is not shown, in fact, by the deformation patterns in machine chips.

Usually the coefficient of friction is merely the ratio between the tangential component on the face of the cutting tool and the normal component, and that normal component can have, and obviously will have, quite a large component of hydrostatic stress, which has no effect on yielding. Coefficients of friction are therefore most unlikely to be as high as even a half in a metal-working process, quite apart from the effect of lubricants, which will again reduce the metal-to-metal contact over the face.

In metal-working and cutting processes the apparent coefficient of friction depends on the nature of the slip line field at the point as to what is, in fact, the relationship between the normal and tangential stresses.

If the tool–chip contact is essentially elastic, then higher coefficients would be possible, but then it is unlikely that the interfacial pressure is as high as 100 tons/sq. in.

Mr. Spear: In regard to the drilling test at which so much criticism has been levelled, the average usage of drills in the U.K. is something like 40,000,000 per year, which is quite a lot of drills. This means that research into the life of drills is reasonably worthwhile undertaking, and the fact that large tests on those drills are not necessarily correlated with turning tests, milling cutting tests, or even grinding tests is irrelevant when related to the percentage of metal usage in the U.K.

In regard to the variation of these tests, I notice in the paper by Morton and Tourret there does seem to be in some of them a much wider variation in life than in the results reported from the B.S.A. group Machinability Research Laboratory. It would infer that the reason is that in some of the Morton–Tourret tests the conditions used and the order of the life obtained was very far removed from normal usage of those tools for which the high-speed steel and its heat treatment was designed. On the other hand, the general order of the life in the B.S.A. tests is much nearer to reasonable commercial practice—in other words, if a $\frac{1}{8}$- or $\frac{3}{8}$-inch drill is being used, it might reasonably be expected to drill several hundred holes, and not merely just ten, twenty, or thirty, before the tool fails. If the tests are exaggerated unbalanced properties relative to practical conditions of tool wear are also tested.

I must stress that whilst I believe in the very fundamental approach made by an earlier speaker in very ingeniously collecting the by-products of metal cutting and analysing them, at the same time we should not lose sight of the opening remarks of the Chairman when he said that the use of cutting fluids with the metal-cutting action was concerned with rate of production, tool wear, finish, and life. Academic interest apart, and knowledge for the sake of knowledge apart, surely the fundamental aim of the majority, in fact, I would say, all of the work in the papers we have been discussing today has been concerned with tool life, tool finish, and greater economy in the shop. Consequently, tests which are a reasonable simulation of workshop conditions, but to which are added normal scientific techniques of control of variables, cannot be regarded in any way as bad techniques, since the fundamental results are the type which will lead to the improvements we are trying to achieve.

A. J. Chisholm: I should like to discuss briefly one difficulty which may be met in obtaining reproducibility in the results of machining tests designed to evaluate the performance of cutting fluids. Recent work carried out at the Mechanical Engineering Research Laboratory showed that the work material would be a very difficult thing to control in this type of test. In a series of tool wear experiments, even though care was taken to ensure that the Brinell hardness and metallographic structure were as constant as possible, very significant variations in small amounts of tool wear measured by means of a micro-technique were observed in a number of ferrous materials for constant cutting conditions and even in the same piece of steel. The largest variations

occurred across the cross-sections of rolled materials. This suggests that any results of tests used for evaluating cutting fluids and expressed in terms of tool life should be quoted in terms of their statistical significance. It is important to know, when there are variations in the tool life found with the same cutting fluid, whether the apparent difference in the means of tool life found with different cutting fluids is actually significant on a statistical basis. In some of the papers several results have been quoted in this way, but by no means in all. It should also be noted that results may have the appearance of validity when their statistical significance is appended, but if the tests have not been carefully performed so that variations in the work material and tool material are randomized among the tests, then this appearance of validity may be spurious.

I should also like to refer to Mr Stabler's comments about the theoretical maximum temperature which is produced in the cutting process. In Table I of his paper he has calculated the mean temperature which the chip would attain if all the heat produced in the cutting process flowed into the chip uniformly. In fact, the frictional heat produced by the chip sliding over the tool face is concentrated in a region of the chip adjacent to the tool face, and this causes the actual temperature which may be attained in this region to be very much higher than the adiabatic temperature which is mentioned by Mr Stabler.

There is a lot of talk about the cooling properties of coolants, but it does appear, on theoretical grounds, that at reasonably high cutting speeds (such as are used in turning) the reduction in chip–tool interface temperature which can be effected by having a cutting fluid in contact with the back surface of the chip is quite small. The rate at which heat can flow across the chip is too slow in comparison with the velocity of the chip. It also appears that differences in the thermal conductivity of different tool materials cannot significantly alter the chip–tool interface temperature. Liquid coolants are probably important when the whole of the wedge of the cutting tool point heats up to a high temperature; the coolant reduces the temperatures in this wedge and prevents complete collapse of the cutting edge as a result of thermal softening.

If the cooling properties of cutting fluids are important, it seems advisable to use water, which is a very good coolant, and relatively cheap, as a standard with which to compare all other cutting fluids. This has been done in some cases in the papers, but not in all, and it would be particularly valuable to see how the efficacy of liquid carbon dioxide, which has been advocated as a metal-cutting coolant, compares with that of water.

Dr D. F. Galloway: The two direct questions addressed to me were those put by Mr Dodd and Dr Clayton. I have no doubt that the tables contained in the "Manual on Cutting of Metals" are valuable, as they are the outcome of many years' work, but I have never made much use of the particular formulæ given in that book.

Dr Clayton referred to the desirability of a general test for cutting fluids. Although such a test would be of considerable value to everyone concerned with metal cutting, the fact remains that it is not practicable to devise a satisfactory general purpose test at the present time. Our knowledge of cutting fluids is still very limited, and an indication of some of the difficulties which are involved in increasing our understanding of the subject has been given at this symposium today. For example, Drs Bowden and Tabor have referred to various complex aspects of the fundamentals of the subject, and Mr Morton and Mr Tourret have discussed the difficulty of ensuring that the man on the shop floor makes better use of the cutting fluids which are at present at his disposal. Many problems remain to be solved in the laboratory and in the workshop, and until we have a better understanding of the fundamentals as well as of the most effective methods of applying cutting fluids, we shall not be in a position to devise a really satisfactory single test for cutting fluids. There are often considerable differences in the performance of different cutting fluids, cutting tools, work-piece materials, etc., in different machining operations. Some indication of the source of these differences is given in the somewhat simplified chart of drilling criteria and factors in the paper by Messrs Morton and Tourret. We have developed similar charts at PERA for turning, milling, grinding, and various other operations. It is very difficult to control and measure these variables, even in a given operation, and I doubt, therefore, whether in the present state of our knowledge a single test can be devised which will take into account all the variables in different processes, and thus give results applicable to all machining conditions. Another reason why it would be difficult to develop a single general purpose test is that research has shown that if a given series of cutting fluids is thoroughly tested in a range of machining operations, such as turning, milling, drilling, etc., fluids which have the best performance in one type of machining operation sometimes give a relatively poor performance in other operations.

WRITTEN DISCUSSION

H. Grisbrook: I would like to refer to the practicability of measuring tool wear by measurement of the amount of metal removed from the tool, when resharpening, by reference to the graduations on the grinding machine dial.

Introduction

The problem of determining the relative merits of two grades of cutting oil in respect to tool life is mainly a question of tool wear, providing other factors remain constant.

The user has the choice of a very wide range of cutting oils, together with the recommendations for their use by the suppliers, but his working conditions rarely align themselves with the laboratory conditions upon which these recommendations are based.

Furthermore, for purposes of economy he is obliged to compromise in his choice of oils by limiting the number of oils stocked. This compromise usually results in an available choice of two, or three at the most, one a cheap general purpose grade and the other a high quality expensive grade.

In practice, therefore, he is faced with the question of deciding which, of two oils, to use for a particular operation under his own specific working conditions, and, when tool life is the main factor, tool wear is the factor to be measured.

Providing tool grinding is not by off-hand methods, then it should be possible to determine the amount of metal removed to resharpen the tool by reference to the graduated feed dial on the grinding machine.

The following trials were carried out with the object of testing the possibility of this method as applied to the single point turning tool.

A Talysurf, with datum attachment, was used in collaboration with the figures obtained from the grinding machine, and it was found that, over the section traversed by the stylus of the Talysurf, the grinding machine figures agreed. But it was much more effective than this, for the stylus traversed only a particular section, which was not necessarily the deepest part of the

abrasion zone, and this was also shown by grinding; so that when the deepest wear was removed the machine dial gave the figure for the maximum amount of tool wear.

Equipment Used

The turning tests were carried out on a 9½-inch centres Monarch, all geared head, centre lathe (Fig B).

The test piece was of En.4. steel, initially 4 inches dia, which was chuck mounted and centre supported at the tailstock to permit a 24-inch length of cut.

As the ultimate purpose of the measurement of tool wear is the selection of a cutting oil, two grades of oil were used. "A" was a straight mineral oil and "B" a sulphurized compounded oil, both supplied by Fletcher Miller Ltd.

The two En.4. test pieces were cut from the same bar, one for each oil, and successive cuts 0·150-inch deep with $\frac{1}{120}$-inch feed were taken at different speeds, the length of cut giving the same amount of metal removal for each speed. The cutting speeds ranged from 184 to 420 s.f.p.m.

The turning tools had zero plan angle, *i.e.* a roller box type of tool, all clearance angles were 5°, the side top rake was 20° and the back top rake zero. The nose radius was 0·050 inch.

All these angles were provided by a tool block, which was mounted on the magnetic chuck of a surface grinding machine (Fig C).

Fig A

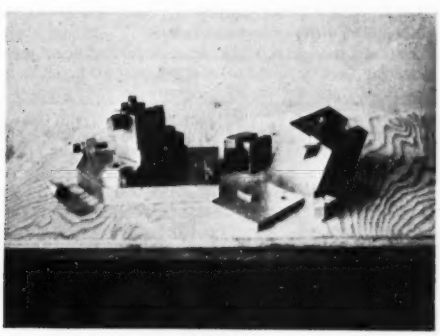


Fig B

The clearance angles are a fixed feature of the block, but for the rake angle the block itself provides 10° and, by means of two sole plates of 5° and 10°, the rake angle can be varied in steps of 5° from −5° to +25°.

This block supported the tool on the Talysurf, and thus presented the tool face concerned horizontally under the stylus. Two stops were provided on the baseplate of the

Fig C

Talysurf to ensure that the trace was taken each time at the same position on the tool surface.

The Conduct of the Experiment

During each test run five Talysurf records were taken at equal intervals along the length of cut; for this purpose the tool was removed from the lathe toolpost and set up on the Talysurf.

The top surface of the tool was indicated by "T" and the flank face by "F."

At the commencement of the trials it was originally intended to use a maximum speed of 257 s.f.p.m.; this, when using oil "A," gave a reasonable amount of wear (0·0004 inch), but at the next lower speed of 184 s.f.p.m. the resultant wear was found to be 0·0001 inch on "T" and negligible on "F."

It was then decided to use still higher speeds of 326 and 420 s.f.p.m., even though it was realized that they were far in excess of practice, but they were necessary to produce wear on the tool comparable with the amount expected in practice at the end of one or two shift periods. This is considered justifiable, as the problem is one of tool wear measurement and not the valid relationships between tool wear and cutting speeds.

Similarly, the relative merits of the two cutting oils used may not be fairly stated, for, to quote Chisholm, "The validity of accelerated tool wear tests for evaluating the effect of cutting fluids on tool life is particularly doubtful because the effect of cutting speed on the behaviour of cutting fluids is so great."

Thus the problem, as stated earlier, is one of the practicability of measuring tool wear, and once this has been established it can then be applied under workshop conditions for the evaluation of cutting speeds and the relative merits of cutting oils.

At the end of each run the final Talysurf record indicated the amount of wear in the path of the stylus. The tool, in the tool block, was set up on the surface grinder and, from the graduations on the machine dial, the depth of cut, which resulted in removal of the abrasion in the line traversed by the stylus, was observed.

In all cases this agreed within ±0·00005 inch with the figure taken from the Talysurf record.

Except for the lower speeds, this amount of grinding did not remove the deeper abrasion zone, which was to one side or the other of the stylus path.

Grinding then proceeded until the evidence of deepest abrasion was removed, and this depth was then recorded from the machine dial.

After the final run of tool Nos. 1 and 2, for Oil "B," grinding was stopped after the removal of the wear evidence in the path of the stylus, and the remaining depth was measured on the Talysurf by suitable location of the tool under the stylus. For tool No. 2 the residual crater was found to measure 0·00045 inch on "T," and on the flank of No. 1 tool it was 0·0002 inch. These figures are given in Table A.

This variation was made so as to justify the figures recorded of the residual crater for the corresponding run with oil "A."

When measuring the wear on F, by grinding, it was found that the Talysurf figure could be 0·00005–0·0001 inch larger than that obtained from the machine dial. This can be accounted for from the order of grinding. Face T was ground first and, by geometry, some portion of the wear on Face F must then be removed, therefore if the stylus, when traversing face F, should locate the point of initial maximum wear, then the amount removed by grinding on face F will be less than the Talysurf record.

The position of maximum wear on face F for the highest speed, using oil "A," corresponded to the periphery of the work, and in this instance the machine dial shows an additional 0·0007 inch for removal of the groove.

Under the conditions provided by the test Fig D indicates that at 257 s.f.p.m. oil "B" shows an improvement over oil "A" of 50 per cent on "F" and 33⅓ per cent on "T," while at 326 s.f.p.m. the improvement is 50 per cent on "F" and 66⅔ per cent on "T." However, as mentioned previously, these figures cannot be directly related to results which may be obtained from those oils in practice when running at normal speeds.

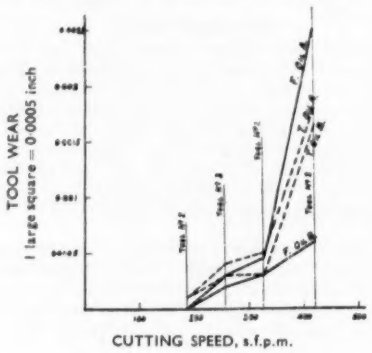


FIG D

A—STRAIGHT MINERAL OIL. B—SULPHURIZED MINERAL OIL. T—TOP FACE. F—FLANK

Conclusions

While the accelerated conditions do not permit a true assessment of the merits of the two oils and the En.4. steel did not afford a suitably severe machining problem

TABLE A

	T = top face of tool F = cutting clearance face	0·150-inch depth of cut, 1/120-inch feed, traverse stopped every inch											
		Tool No. 3						Tool No. 2					
		4-inch-dia bar 20·2 inches long at 245 r.p.m. = 257 s.f.p.m.						4-inch-dia bar 3·8 inches long at 186 r.p.m. = 195 s.f.p.m. 3·7-inch-dia bar 17·9 inches long at 186 r.p.m. = 181 s.f.p.m.					
		T			F			T			F		
		T_I	T_G	$T_I - T_G$	F_I	F_G	$F_I - F_G$	T_I	T_G	$T_I - T_G$	F_I	F_G	$F_I - F_G$
Oil A	Machine dial: Grind to clear along stylus path	82·3	82·7	0·0004 *	81·0	81·3	0·0001 *	75·2	75·3	0·0001 *	Negligible wear		
	Machine dial: Finish grind	—	—	—	—	—	—	—	—	—			
	From Talysurf trace	—	—	0·0004	—	—	0·0003	—	—	0·0001			
Oil B	Machine dial: Grind to clear along stylus path	95·7	96·0	0·0003 *	92·8	93·0	0·0002*	90·7	90·8	0·0001 *	Negligible wear		
	Machine dial: Finish grind	—	—	—	—	—	—	—	—	—			
	From Talysurf trace	—	—	0·00025	—	—	0·00025	—	—	0·0001			

	T = Top face of tool F = Cutting clearance face	0·150-inch depth of cut, 1/120-inch feed, traverse stopped every inch											
		Tool No. 2						Tool No. 1					
		3·7-inch-dia bar 6·1 inches long at 390 r.p.m. = 378 s.f.p.m. 3·4-inch-dia bar 17·3 inches long at 494 r.p.m. = 440 s.f.p.m.						3·4-inch-dia bar 6·7 inches long at 390 r.p.m. = 34·7 s.f.p.m. 3·1-inch-dia bar 19 inches long at 390 r.p.m. = 318 s.f.p.m.					
		T			F			T			F		
		T_I	T_G	$T_I - T_G$	F_I	F_G	$F_I - F_G$	T_I	T_G	$T_I - T_G$	F_I	F_G	$F_I - F_G$
Oil A	Machine dial: Grind to clear along stylus path	80·2	81·0	0·0008	83·9	85·7	0·0018	86·8	87·0	0·0002	83·0	83·4	0·0004
	Machine dial: Finish grind	80·2	82·0	0·0018 *	83·9	86·4	0·0025 *	86·8	87·3	0·0005 *	83·0	83·4	0·0004
	From Talysurf trace	—	—	0·00075	—	—	0·00175	—	—	0·0002	—	—	0·00045*
Oil B	Machine dial: Grind to clear along stylus path	4·0	5·2	0·0012	8·1	8·7	0·0006 *	24·2	24·4	0·0002	Grinding of T removed the wear in path of stylus		
	Machine dial: Finish grind	—	—	—	—	—	—	24·2	24·5	0·0003 *			
	From Talysurf trace	—	—	0·0012	—	—	0·0006	—	—	0·0002	—	—	0·0001
	Instead of "Finish Grind" the position of maximum wear was located and measured by Talysurf			0·00045							—	—	0·0002
			Total :	0·00165*								Total :	0·0003 *

* Figures used for graphs.

to bring out the qualities of the sulphurized oil, the method of wear measurement by the grinding machine dial was sufficiently sensitive to indicate a difference between the two oils.

The comparison with the Talysurf substantiated the readings from the grinding machine and emphasized the advantages of the grinding method. The pattern of wear could be assessed as grinding proceeded, and the depth of the deepest crater was always determined. In addition, the built-up edge presents difficulties for the Talysurf, but it does not interfere with the grinding method.

Its application in practice will require a surface grinding machine with a micrometer feed, a standard feature on most 8 × 16-inch surface grinders, and it will be desirable to provide a grinding block or some such reliable method of reproducing the tool angles when grinding.

The question of validity of the percentage figures derived from these trials have been stressed in regard to the accelerated nature of the tests; it should also be emphasized that these figures result from only a small number of samples and for a more reliable determination to be made, a larger number of tools should be used with each oil and cutting speed, and the results should then be assessed statistically.

J. P. Brown and A. M. Laws: The efficiency of a cutting fluid is usually estimated in practice from its effect on tool life and the surface texture of the machined component. Cutting forces are of little importance in themselves as a practical criterion of tool performance.

Most of the observed effects of cutting fluids which are attributed to some form of lubrication arise at comparatively slow cutting speeds. Under these conditions the built-up edge can control the tool life and surface texture in many operations. Much could be learned by studying the changes in tool life and surface texture arising from changes in the magnitude and other characteristics of the built-up edge. Not only the cutting fluid, in liquid or gaseous form, but also the chip dimensions and the cutting speed would have to be considered.

There is already evidence to suggest that cutting fluids can have opposing effects on tool life and surface texture, an improvement in one taking place at the expense of the other. This phenomenon is very marked in reaming operations on mild steels. Work by Morton and Tourret (reported in their paper) and by our laboratory has shown similar trends in low speed turning operations. On such operations the function of a cutting fluid may be to control the built-up edge characteristics to obtain an improvement either in tool life or in surface texture.

The greater importance of the built-up edge of clearance face wear may be judged from Figs 3 and 4 of Stabler's paper. The built-up edge can prevent contact between the clearance face of the tool and the cut surface of the work, but not between the chip and the rake face.

As consumers of cutting fluids we should like to endorse Grisbrook's remarks on the economic aspects of their application. It is increasingly difficult to make decisions on the use of cutting fluids when confronted with the wide variety that is available. A simplification would be most welcome. A range of three fluids is as much as any one consumer can afford to handle for general purpose machining. A clear definition of the composition and performance of three or four fluids representative of the known major groups of cutting fluids is needed.

G. D. Galvin and R. Tourret: We are very interested in the investigation made by Wolfe, Kinman, and Lennard into the effectiveness of various chlorinated hydrocarbon compounds as cutting oil additives. As far as we know, these are the first practical machining results to be published of British work on this particular subject, and they afford interesting comparison with American * and Russian † work of a rather different character on the same type of compounds.

On the face of it, the coefficient of friction measured between the chip and the tool face when turning aluminium, as was done in the American work,* would not be expected to correlate with tool life when drilling steel. However, in this instance we are concerned with a series of additives of similar type in which the active element is the same, blended into a single base oil such that all the test blends are of about the same viscosity. In these circumstances, it might be thought that the main factor which would decide the effectiveness of the blend would be the chemical reactivity of the additive, which in one instance would affect friction and in the other instance tool life. In fact, comparing the two sets of results, a low value for friction generally corresponds with a long tool life. The exceptions are pentachorethane and dichlorethylene, which gave better drill lives than would be expected from the friction results.

It is said in the paper that the maximum effectiveness is obtained with a relatively low concentration of additive. The results on ethylene dichloride (Table V) show that tool life decreases if that optimum concentration is exceeded. This seems surprising to us, since our limited experience ‡ indicates that while there may be an optimum point, performance does not fall off when this is exceeded, but merely remains at the same level. Also, there is little doubt that neat carbon tetrachloride is an extremely effective cutting fluid as regards tool life, and that it would be widely used in industry but for its toxicity and other disadvantages. Surely this would not be so if its activity decreased with increasing concentration.

It would be very interesting if Wolfe and his colleagues could find time to test more of these additives at various concentrations. This effect of concentration does not appear to be entirely straightforward, and it is certain that more remains to be learnt on this subject.

We are interested to learn that such a small change in bulk oil temperature as 7° C had such a large effect on the drill lives obtained. We have performed a series of drilling tests at Thornton on a neat oil (see Table IV of paper by Morton and Tourret for test conditions) in a manner deliberately chosen to aggravate such a temperature effect. Tests were performed in rapid succession using a viscous oil without altering the setting of the relief valves during the tests. Thus, as the oil warmed up and its viscosity fell, the flow rate increased. The beneficial effect of increasing the flow rates is well known but the actual quantitative effect on the drilling test used at Thornton can be seen from Fig 1. Thus in the tests in which the relief valves were not disturbed and the flow rate consequently increased, longer drill lives would be expected. The results, which are given in Fig 2, show the expected effect, the same effect as mentioned by Wolfe and his co-workers, of increasing tool life with higher oil temperatures. However, the significant feature is that the effect was not nearly so pronounced, especially when it is considered that in their tests the lubricant flow was maintained constant, whereas in the Thornton tests this was deliberately allowed to increase. Possibly the very large effect noted by Wolfe was due to the very small concentrations of additives used. As the temperature was increased, the vapour pressure of the dichlorethylene would increase, and this might have the same effect as an increase in concentration. Mr Wolfe has already shown that a slight increase in concentration at the low levels has a great effect on tool life.

* Shaw, M. C. *Ann. N.Y. Acad. Sci.*, 1951, **53**, 962.

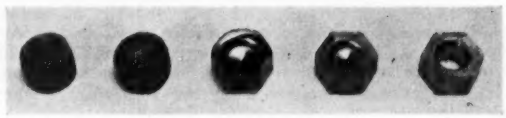
† Pleteneva, N. A., and Epifanov, G. I. *Doklady Akademii Nauk SSSR*, 1951, **77**, 1051.

‡ Tourret, R. Contribution to the discussion on "Recent developments in the machinability of steel." *Proc. Instn Mech. Engrs, Lond.* (to be published).

Finally, although we have perhaps been a little critical in our contribution to the discussion, we would emphasize that Mr Wolfe and his co-workers have been the first to report the results of practical machining tests on these additives and that their work has been very valuable and interesting. It is only through such efforts that the full mechanism of cutting oils and additives will be understood.

R. Tourret: Nuts are usually associated with bolts—for this reason I present Fig E (*a*) and (*b*), which show, for the record, comparable stages in the forming of nut blanks as illustrated for bolts in Fig 1 of Mr Townend's paper. The two figures show the chamfered and the flat sides respectively of a nut. In the first operation, a piece of rod is sheared off and partly formed; in the second it is more fully formed and the hexagonal started; in the third a start is made on punching a hole, the hexagonal outer contour is finished, and the chamfer is formed; in the fourth the faces are flattened; and in the fifth the centre is punched out to leave a nut blank ready for tapping in a separate machine.

(*a*)



(*b*)

FIG E

STAGES IN FORMING A NUT BLANK. (*a*)—CHAMFERED SIDE, AND (*b*)—FLAT SIDE

REPLIES TO DISCUSSION

Dr F. P. Bowden and Dr D. Tabor: In answer to Dr Barwell's comment on Fig 3, the process involved may be described as a sort of ploughing in which a fresh surface is exposed on the right-hand side of the groove while displaced material is thrown up as a parapet on the left. We are not sure whether it is wrong to call this a cutting process.

As far as Fig 2 is concerned, Dr Stabler's interpretation of it is fairly reasonable in view of the rather poor reproduction, but actually a more detailed photograph at higher magnification shows that the chatter is in no way connected with the original surface irregularities. It corresponds to small-scale stick–slip motion which has been described earlier. It should be emphasized that it is a typical friction track produced by the sliding of metals. There is some grooving accompanied by a continuous formation and shearing of intermetallic junctions.

The practical significance of the results of cutting in different gaseous atmospheres has been mentioned by a number of speakers. We would ourselves like to emphasize and have stressed in the original paper the need for caution in assessing the practical significance. These few experiments—literally a scratching at the surface—were made as an attempt to approach in a more fundamental way one aspect of the action of cutting fluids. We wished to separate the cooling from the lubricating action of the cutting medium. The experimental results quoted, admittedly of an exploratory nature, indicate that even when the cooling action is negligible a suitable vapour can produce a very marked improvement in surface finish and a reduction in pick-up on the tool: the frictional aspect is obviously important.

In reply to some of the points raised by Dr Chisholm, we may mention that since the paper was written a few experiments have been carried out in an atmosphere of CO_2 at room temperature; the results indicated that under our conditions there was little improvement in surface finish. On the other hand a steam jet appeared to give very good surface finish.*

Finally, we should like to say something about the basic mechanism of the cutting process. Undoubtedly the work of Ernst and Merchant has played a pioneering part in clarifying some of the first principles of the cutting operation, but there are several factors which make it inadequate. First is the role of combined stresses in producing plastic flow of the chip. It is not valid to treat the normal pressure on the tool face and the frictional force as two independent forces; as Professor Ford pointed out, these two play a conjoint part in determining the conditions under which plastic flow of the chip will occur. As a direct problem in plasticity this has not yet been satisfactorily solved in spite of the interesting analysis of Lee and Shaffer.† Another factor is the effect of temperature on the mechanical properties of the metal being cut. Not only are the surface temperatures very high—as Trent's work shows ‡ at high-speed cutting they may well exceed 1200° C—there is also a marked temperature gradient through the chip itself. The elegant treatment of Ernst and Merchant can thus be accepted only as a crude compromise with the true state of affairs. We hope that experts in plasticity and metal deformation processes will be able to carry the analysis a stage further. Out of this may well emerge a more basic and more effective approach to the problem of devising better and more efficacious cutting lubricants.

M. D. Kinman: The speakers commenting on the B.S.A. paper have confined their remarks to the need for a more fundamental approach, together with criticism of the validity of the results of the tests. It has been suggested that the results should be expressed in terms of their statistical significance. Surprise has also been expressed at the marked improvement in performance resulting from a relatively small increase in oil temperature and at the effectiveness of pentachlorethane and dichloroethylene as additives. The encouraging remarks given to the paper have been gratefully noted, and it is the intention of the authors to continue their work in this field.

Regarding the need for more fundamental research, this is undoubtedly desirable, but the problems are so complex and so difficult to tackle that results cannot be expected for some time. Meanwhile comparative practical tests are giving results of great value.

It is also considered that much of the fundamental work which has already been done is only of academic interest because it has been done outside the limits of ordinary practical application, for example tests have been made at cutting speeds much lower than those normally in use in the industrial field, and it has been found that tests which are either accelerated by using abnormally high cutting speeds or extended by using low cutting speeds tend to give very scattered results. There are also indications that at extremes of speed very

* Bowden, F. P., and Priddle. To be published.

† Lee, E. H., and Shaffer, B. W. *J. App. Mech.*, 1951, **18**, 405.

‡ Trent, E. M. *Proc. roy. Soc.*, 1952, A**212**, 467.

slight variations in either the cutting tool or the test log can have a very marked effect on tool life. At high speeds variations in the tool, even the differences met within a single tool of normal quality, can cause a certain amount of scatter, whilst at low speeds the variations met within the test log can cause differences in performance which are violently scattered. If, however, these extremes are avoided consistent and repeatable results are obtainable which are of immediate use to industry.

There can be little doubt as to the validity of the B.S.A. tests due to the consistent repeatability of the results. This is due entirely to the pains taken to eliminate such variable factors as poor quality drills and test logs.

Statistical control of such tests has, however, been carried out, and full details are given in a recent paper.* Conclusions that can be drawn from this paper are that all factors are under complete control, provided inspection of certain of the elements of the test are carried out according to the instructions laid down in this paper, and it is entirely with this knowledge as a background that the B.S.A. cutting fluid test has been devised.

G. V. Stabler: I agree entirely with Mr Chisholm's remarks. The adiabatic maximum temperature is only a calculation which is of value in giving us an approximate impression of the actual temperature under which cutting occurs. Practical tests do, however, show that it is a good average guide.

I agree with him that the adiabatic maximum may be exceeded locally because the deformation in the chip is not uniform. In addition to the shear caused at the shear plane there is a marked degree of additional deformation at that part of the chip in contact with the tool. It is small at first near the shear plane and increases as the chip flows over the built up edge and across the rake face of the tool. Many microphotographs of the underside of chips show higher degrees of this flow than is shown in the upper left of Fig 2, p. 257. The extra heat generated by this secondary deformation would cause a much higher local temperature were it not for the fact that it occurs near the conductive rake face of the tool.

This secondary deformation is in part the answer to Professor Ford's contribution. In the machining of ductile materials it is common for the metallic grains to be drawn out practically tangentially to the surface in both the undersurface of the chip and in the finished machined surface. Under such plastic flow conditions, coefficients of friction of the order of unity have been measured, and they have been recorded in other fields than in metal cutting.

In giving "specific pressures" of the order of 100 tons/sq. in. attention was drawn to the artificial nature of the conception, particularly because the undeformed chip area was used. The actual local intensity of pressure will be affected by the larger actual area of contact and by the considerable variations of pressure over the area.

I. S. Morton and R. Tourret: We should like to refer first of all to the various speakers who mentioned surface finish. Dr Barwell commented on the performance of a cutting oil containing a sulphurized mineral oil, and rapeseed oil which, despite very smooth cutting, did not give the best tool life. We were interested mainly in roughing operations at the time of the tests quoted, but later we compared a somewhat similar range of cutting oils by a series of turning tests in which surface finish was measured, and the blends containing rapeseed oil were found to differ little from the others.

In reply to Mr Bingham, though the tests referred to in our Table VII were undertaken to answer specific queries, the cutting conditions chosen in each case were based on well-known recommendations, and the results should therefore apply to general good practice for the materials concerned. We regret that our rather brief remark on the relationship observed between tool life and surface finish appears to have misled Mr Bingham. We were referring to the average surface finish for each test (obtained by taking measurements at equal intervals along the cut) and not to variations during the course of particular tests. It was found that for the considerable variety of oils tested, those giving the longest tool life gave the poorest surface finish, and vice versa. Since the overall range of surface roughness in all these tests was not excessive the practical importance of these results should not be exaggerated, and the principal interest to us was the support given to a theory first put forward some ten years ago about the influence of the built-up edge. It is generally agreed that for the best surface finish you must have the minimum of build-up, but it is also reasonable to suppose that a moderate amount of build-up can protect the nose of the tool, *e.g.* from abrasion, and the corrosive effect mentioned by Dr Clayton, and thereby prolong tool life. It may therefore be impossible to obtain optimum values of tool life and surface finish simultaneously. We should like to add that we were very interested by Mr Bingham's contribution and should be glad to hear further details of his work.

In the discussions as a whole considerable interest was shown in surface finish and, bearing in mind the close relation between the cutting action of a tool and the finish of the workpiece, this was well justified. However, it has been our experience that there is less interest now from the workshop side in surface finish; tool life (particularly in roughing and semi-finishing operations) is the main interest, and this has led to the emphasis being placed on tool life in our paper. It may be that the widespread use of grinding for final finishing of many components has caused this apparent decline in the interest in surface finish in other operations, and comment from production engineers on this point would be welcome.

We do not quite understand Mr Spear's remarks on small numbers of holes, since the test conditions were always chosen so that the best oils in the various series (which were the ones we were most interested in) gave lives of about 100 holes or more, and all our experience tends to confirm that, as originally suggested some years ago,† such a number is adequate. If, as Mr Spear implied, our cutting conditions were nevertheless considerably different from normal usage, it would be justifiable to conclude that normal usage is failing to make full use of the potentialities of modern machines, cutting tools, and cutting oils. It is true that some of our results do not show the remarkable repeatability quoted for the B.S.A. test, but it must be emphasized that our test was designed for use with several operators, whereas we understand that in the B.S.A. test a single experienced operator must be employed. Most important of all, all workpieces at Thornton were completely randomized. This sometimes led to results apparently more variable than those obtained when workpieces were not randomized, but our experience has amply confirmed Mr Chisholm's contention that unless this is done an "appearance of validity may be spurious." Before comparing methods further, therefore, it would be desirable to know if this was done in the tests which Mr Spear had in mind.

We have just mentioned our agreement with Mr Chisholm that workpieces and tools must be fully randomized if valid results are to be obtained. We further agree that results should be subject to tests of statistical significance, and it is our usual practice to do so for all tests (as shown, for example, by Fig 3 of the paper).

Finally, considering the general selection and application of cutting fluids, we feel that the views expressed by

* Wolfe, K. J. B., and Robinson, I. R. *Metallurgia*, 1951, **43**.

† Galloway, D. F., and Morton, I. S. "Practical Drilling Tests," Inst. of Prod. Eng. Research Dept., 1946.

Dr Clayton and Messrs Grisbrook, Brown, and Laws are unduly pessimistic. Referring first of all to Dr Clayton, we cannot accept his statement that cutting oil manufacturers have not tested all of their products in a practical way. While we certainly have not tested all of our cutting oils for all possible applications on all possible materials, they have nevertheless been subject to tests on a sufficient range of operations on metals typical of the most important groups, *e.g.* carbon steels, medium alloy steels, high alloy steels of the stainless and gas turbine groups, yellow metals and light alloys, to give a clear general picture of their capabilities.

Regarding the plea by Messrs Brown and Laws for a range of three cutting fluids to cover all general machining requirements, we feel that if they mean over the whole industry it is unlikely that this ideal can be realized. Oil suppliers do not want only to increase the number of oil cutting oils available—in fact, they would prefer the reverse—but they must meet the demands of users. If maximum efficiency is essential in every phase of machining, more than two or three oils are essential. However, it does not necessarily follow that they will all be necessary in a particular factory: good performance and overall economy may be obtained with a restricted number. In fact, many large factories do operate with only three or four, and others could no doubt do so if they discussed the matter with the supplier.

H. Grisbrook: Dr Galloway suggests that workshop tests are totally unreliable because they are not under controlled conditions. That there are so many uncontrolled variables is perfectly true; no one is saying it is not so. It is accepted that the pure, academic approach is the real way, with scientifically controlled experiments, of making steady and certain progress. But when that steady progress has been made and the reasons analysed for what takes place, it is no use shutting our eyes to the fact that the man in the shop is not getting the benefit from it.

Obviously, from the figures given by the Ministry of Supply speaker, Mr Langston, the sale of oil today depends solely on salesmanship—and not its working value. What is urgently needed is some means by which the man in the shop can test whether what the salesman said was right.

The man in the shop is concerned with tool wear and surface finish, and, as mentioned in the paper, if he can be given anything that will help him to put a yardstick on the effectiveness of the oil he is using, it will be of more use to him than telling him that the analysis was absolutely right under controlled conditions.

It is acceptable that tool wear is a function of tool life and, as the man in the shop will have to grind his tool, he may as well measure the amount of metal he removes and record that as the proportion of total tool life available; that will be his measure when deciding whether the salesman was right.

Without such a measure being made available, to be applied under these despised working conditions, I do not see that any useful purpose can be served by giving the user profound data showing how the oil he is buying behaved under ideal test conditions which he is never likely to meet.

A. J. Chisholm: It has been suggested that not only is it useless to look for a single evaluation test for cutting fluids (as I suggested in my paper) but that the subject is so complicated that an evaluation test is needed for every type of machining operation—for turning, for milling, for tapping, and so on. This seems to be too pessimistic, for one could extend the idea to evaluation tests for slow-speed turning and for high-speed turning, for turning ferrous materials and for turning non-ferrous materials.

How valid would such tests be? The ASTM tests based on tool wear (which I described in my paper) show, as Dr Barwell has pointed out, a most disturbing state of affairs. Even with a single evaluation test, carefully defined and carried out by a number of qualified laboratories, statistically significant results could not be obtained in spite of the extensive precautions which were taken to ensure control of the test conditions.

In this programme it was found that though, in a single laboratory, reproducible results might be obtained, when the results were compared with those of other laboratories the results were found, in some cases, to be statistically not significant. The conclusion from the tests was that it was only possible to distinguish between the major groups of cutting fluids.

Mr A. L. H. Perry has described in the discussion a rather similar state of affairs in some tests with which he was connected, and he has suggested that the source of the variations observed in the tests mentioned by Mr R. P. Langston was the test method itself. Mr Perry has also mentioned some field tests in which variations in tool life of 14 : 1 were found with the same oil, and in which the tests as a whole appeared to show no significant difference between a range of soluble oils. I suggest that we should conclude from all this that efforts should be made to refine one or two tests to the stage when reliable results can be obtained.

The importance of the work of the ASTM in organizing well-controlled co-operative test programmes should be recognized, and it will be of great interest to follow their future progress. One naturally wonders, however, whether, even if an extremely refined laboratory technique is developed which is able to discriminate between cutting fluids within a group, the results would really be important in the workshop. It may be that cutting fluids within each group behave much in the same way for practical purposes.

Dr Clayton refers to the fact that the results of evaluating cutting fluids by means of a cutting force test and a tool wear test do not agree. This is not really surprising. Effective lubricants—those which reduce the chip–tool friction coefficient and hence the cutting force—are chemically active, and because they are chemically active they are likely to increase the rate of tool wear. They do, however, improve the surface finish on account of their effect on the built-up edge. I understand that, in practice, when a cutting fluid salesman finds he has too much "activity," *i.e.* when the tool wears too rapidly, he dilutes the oil with a straight mineral oil until a reasonable compromise is achieved.

Dr Barwell has drawn attention to the difference between the results found in drilling and turning tests. This may be due to the influence of cutting speed—the active constituent having little influence at higher cutting speed—or it may be due to the importance in drilling operations of lubricating the flutes and the lands of the drill—factors which are not met in turning operations. Extreme pressure lubricants which would effectively perform these functions in drilling may have a deleterious effect in turning.

The following two laboratory evaluation tests would enable reasonably accurate predictions of the behaviour of a cutting fluid in practical machining operations. One test evaluates the lubricating function of the fluid at different cutting speeds, *i.e.* the amount by which it reduces chip friction. This could be done by measuring the resultant cutting force in an orthogonal cutting operation—such a test would be more satisfactory than the use of the extreme-pressure testing machine. The other test determines the effect of the fluid on cutting tool wear in an orthogonal cutting operation and its dependence on cutting speed. The results of the first test would suggest how the fluid affects the surface quality, and the second how it affects tool life.

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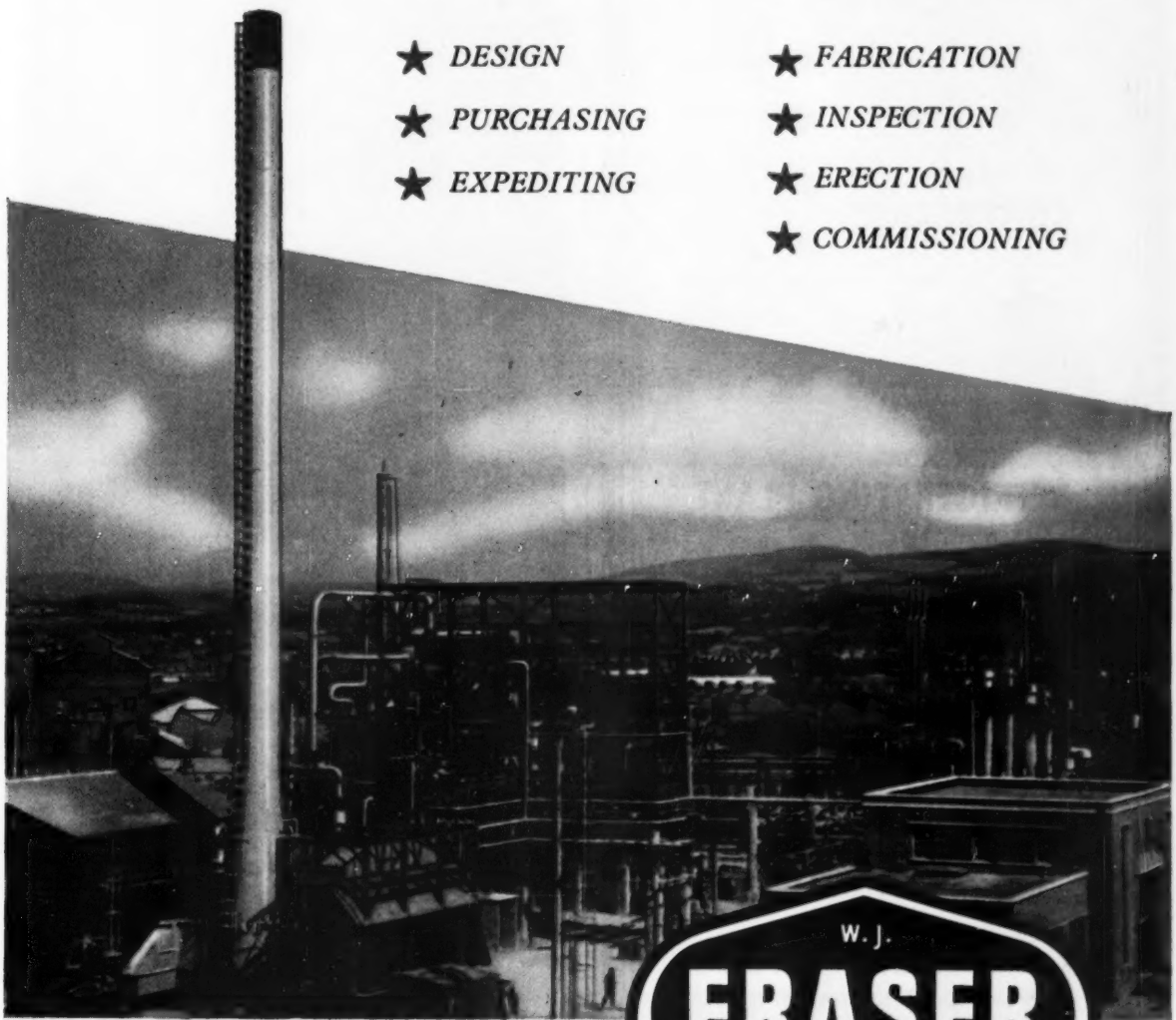

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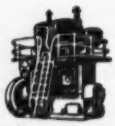

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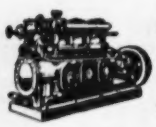

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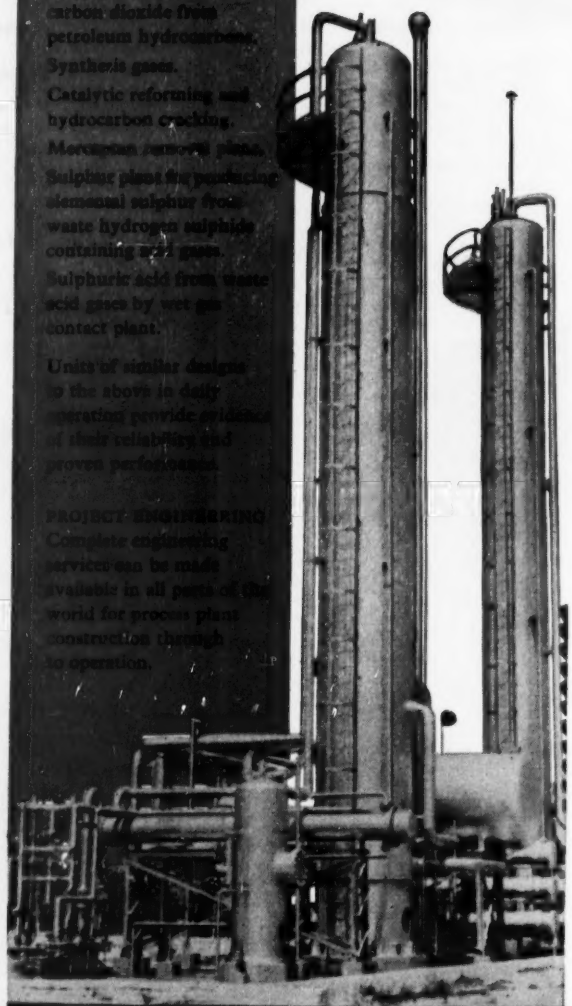

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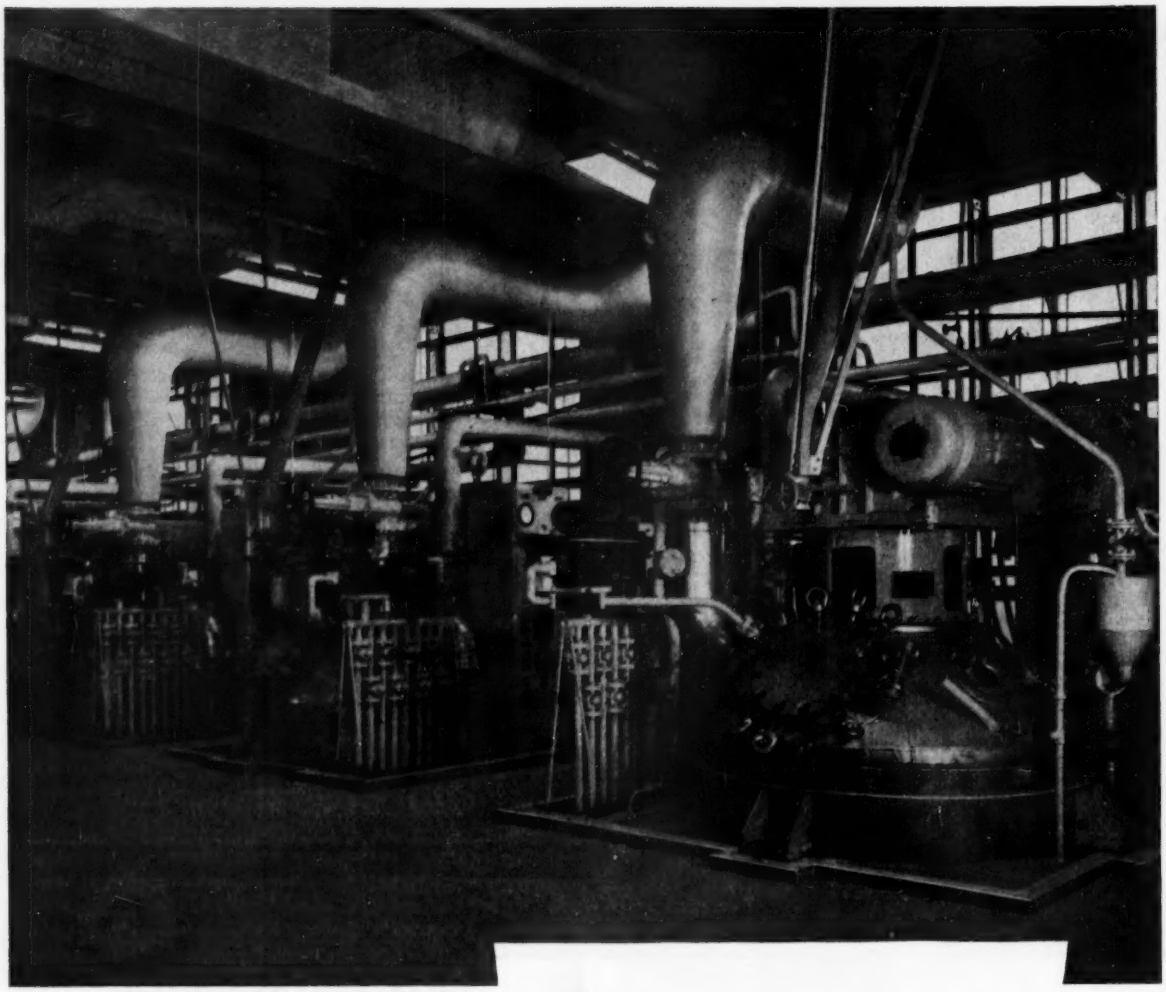

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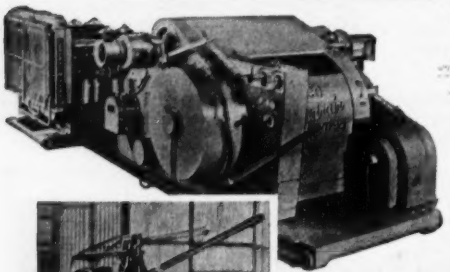

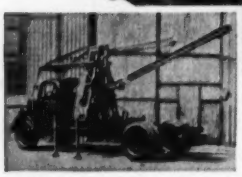

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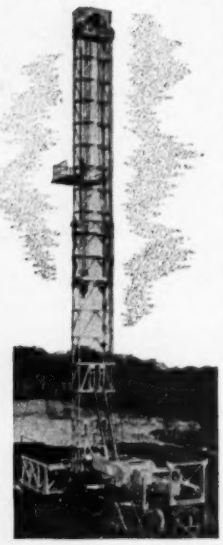

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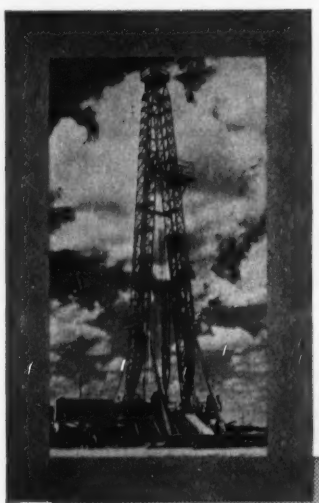

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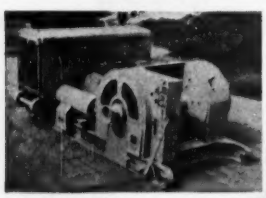

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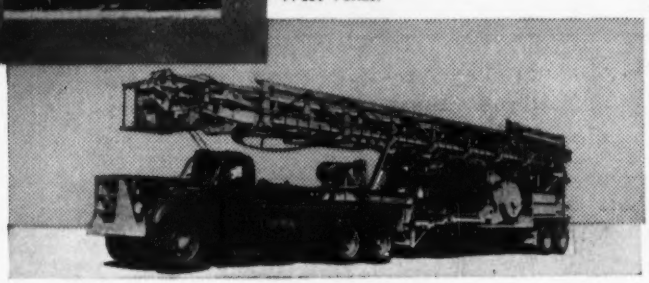

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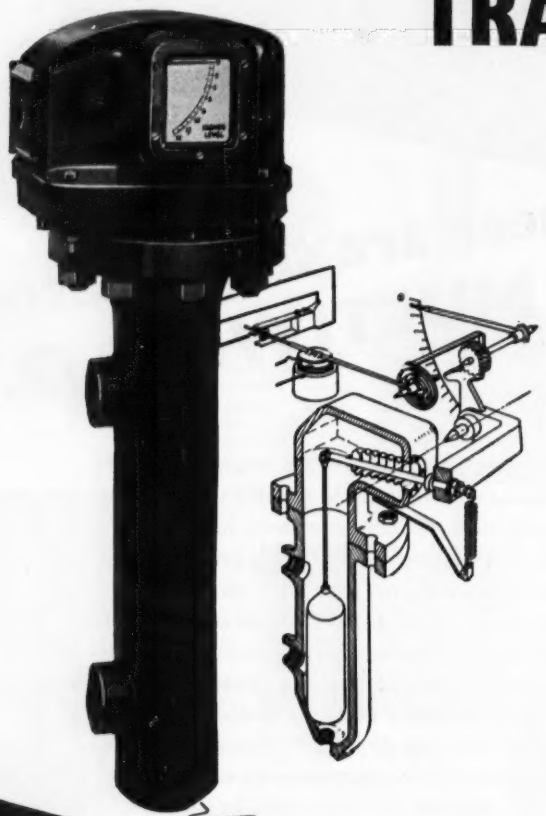

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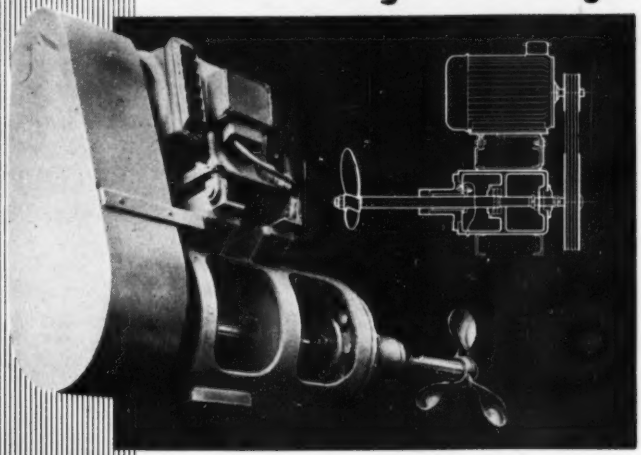

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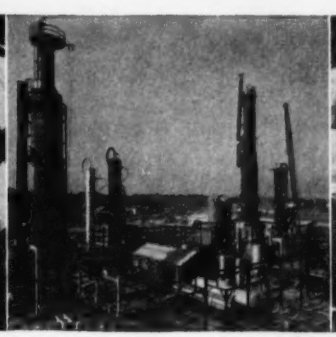
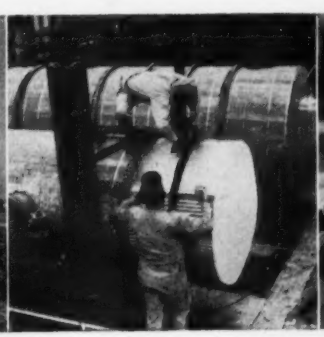

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New Cat Cracker Placed in Operation By Premier

By R. P. Hargis, President
Premier Oil Refining Company of Texas
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PREMIER Oil Refining Company of Texas recently completed a multi-million dollar expansion program at Fort Worth, Texas, making our refinery there one of the most modern in the entire Southwestern area.

R. P. Hargis

The expansion program was rounded out April 10 when a 3,000 B/SD UOP Fluid Catalytic Cracking unit of the latest design went on stream. It is designed to crack blended atmospheric and vacuum gas oils at a conversion rate of 74 per cent into gasoline having 92 clear research octane rating.

Installation of the cat cracker, with its attendant new polymerization and gas concentration facilities—all three of which were designed and licensed by Universal Oil Products Company—brings to six the number of major processing units in operation at the Fort Worth refinery. Others are a UOP Platforming unit, which has a design capacity of 1,500 B/SD, a thermal cracker, and a crude unit. With these facilities, the Fort Worth refinery has now become self-sustaining. Its supply of crude oil is piped from the Ranger Field into Fort Worth.

Four Reasons for New Unit

Four major factors motivated our thinking about installing a cat cracker less than three years after the company built the UOP Platforming unit. These factors were, in brief:

1. A cat cracker would enable Premier to make greater amounts of high quality finished gasolines; it would open up new avenues for marketing such products as butane-butylene; it would put Premier in the position of converting excess middle distillates into marketable products.

2. It would provide not only the Fort Worth refinery but Premier's other Texas refineries at Arp, Baird and Longview with a choice gasoline blending stock having an F-1 leaded octane number of 98 to 100.

3. It would further improve the refinery's economic position by making possible a larger gasoline yield from the crude run. The overall gasoline yield at the Fort Worth refinery was 52 per cent. It was estimated that with a cat cracker a gasoline yield of 67 per cent could be obtained—an estimate that since has proved to be accurate.

4. A cat cracker would permit operating the refinery at its crude oil capacity of 7,500 B/CD.

Coincident with the unit going on stream, Premier launched an intensive newspaper, radio and TV advertising campaign to introduce its new "Ignition Controlled" ethyl gasoline and "Dynamic" regular gasoline. We are now producing a 95 octane premium gasoline and an 86 regular motor fuel to meet the ever-increasing demands for higher quality gasolines in our trade territory.

We supply approximately 100 independent jobbers and more than 600 retail outlets in an area extending from Shreveport, La., on the east to Abilene, Texas, on the west, and from the Red River on the north to the central portion of Texas on the south.

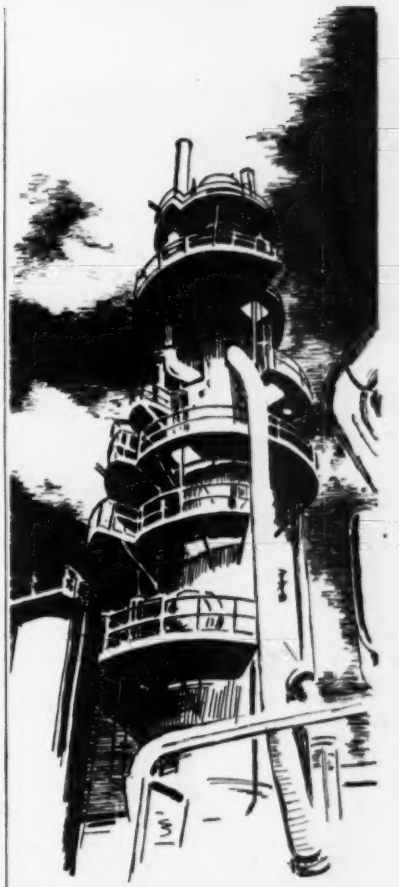
Octane Ratings Increased

Gasoline from the cat cracker is being transported to the Arp, Baird and Longview refineries for use as blending stock. This enables these plants to increase their octane ratings, and puts them in a more advantageous position to meet changing market conditions.

One of the unusual features of our new cat cracker is the placement of the reactor-regenerator on a structural steel skirt instead of having it mounted on a concrete base. Another interesting feature is the suspension of the air heater beneath the regenerator.

All of the pumps and the gas compressors are located under a reinforced concrete structure extending across the battery area parallel to the line of towers. Most of the heat exchangers, surge drums and receivers are placed on the roof of the concrete structure. This arrangement makes for compactness and maximum utilization of space, and enables our operators to control the unit with ease.

With the cat cracker now on stream, we are confident that the Fort Worth refinery is equipped to meet a wide variety of marketing conditions more profitably and with a greater degree of flexibility than was ever possible before.



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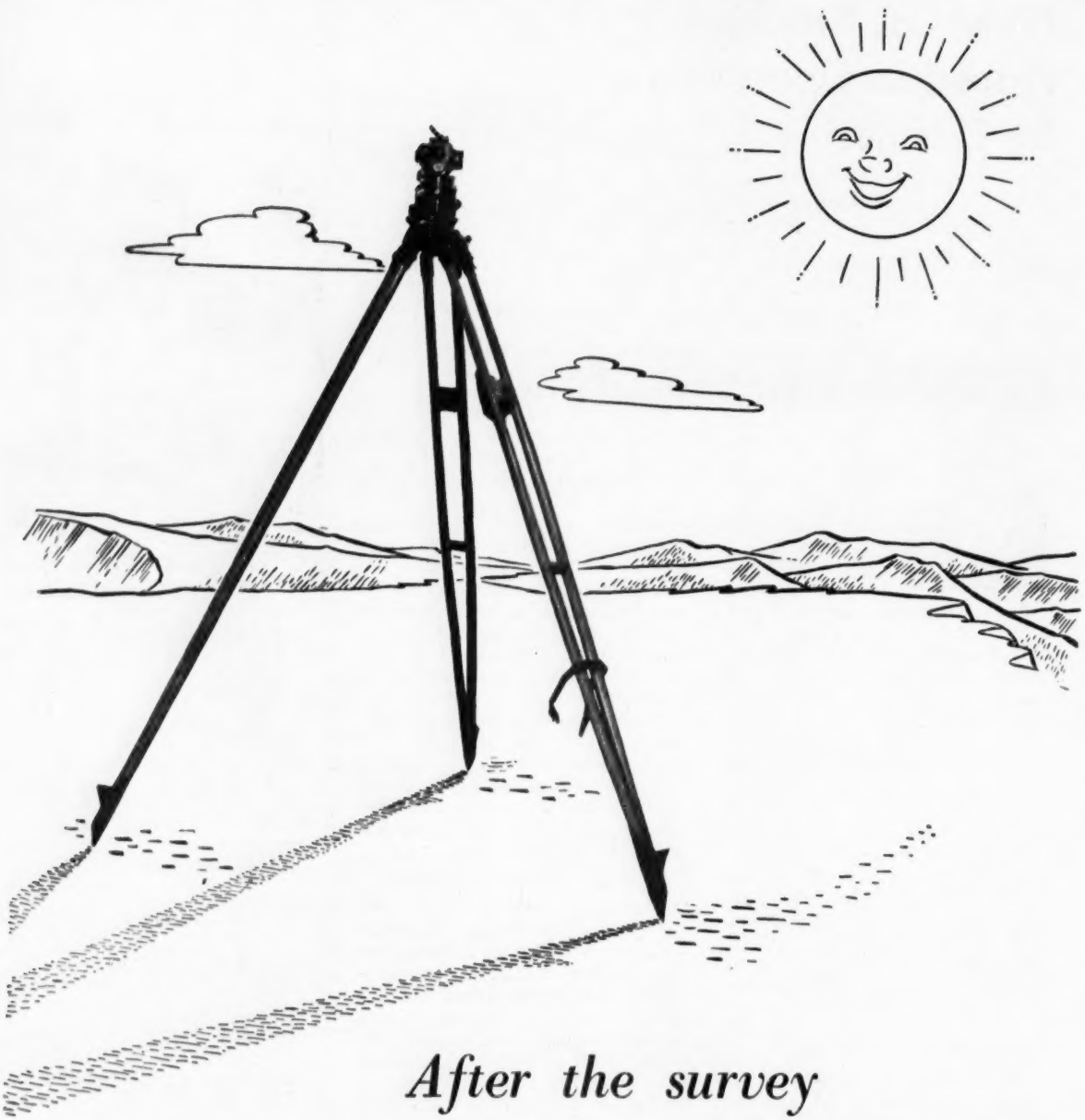

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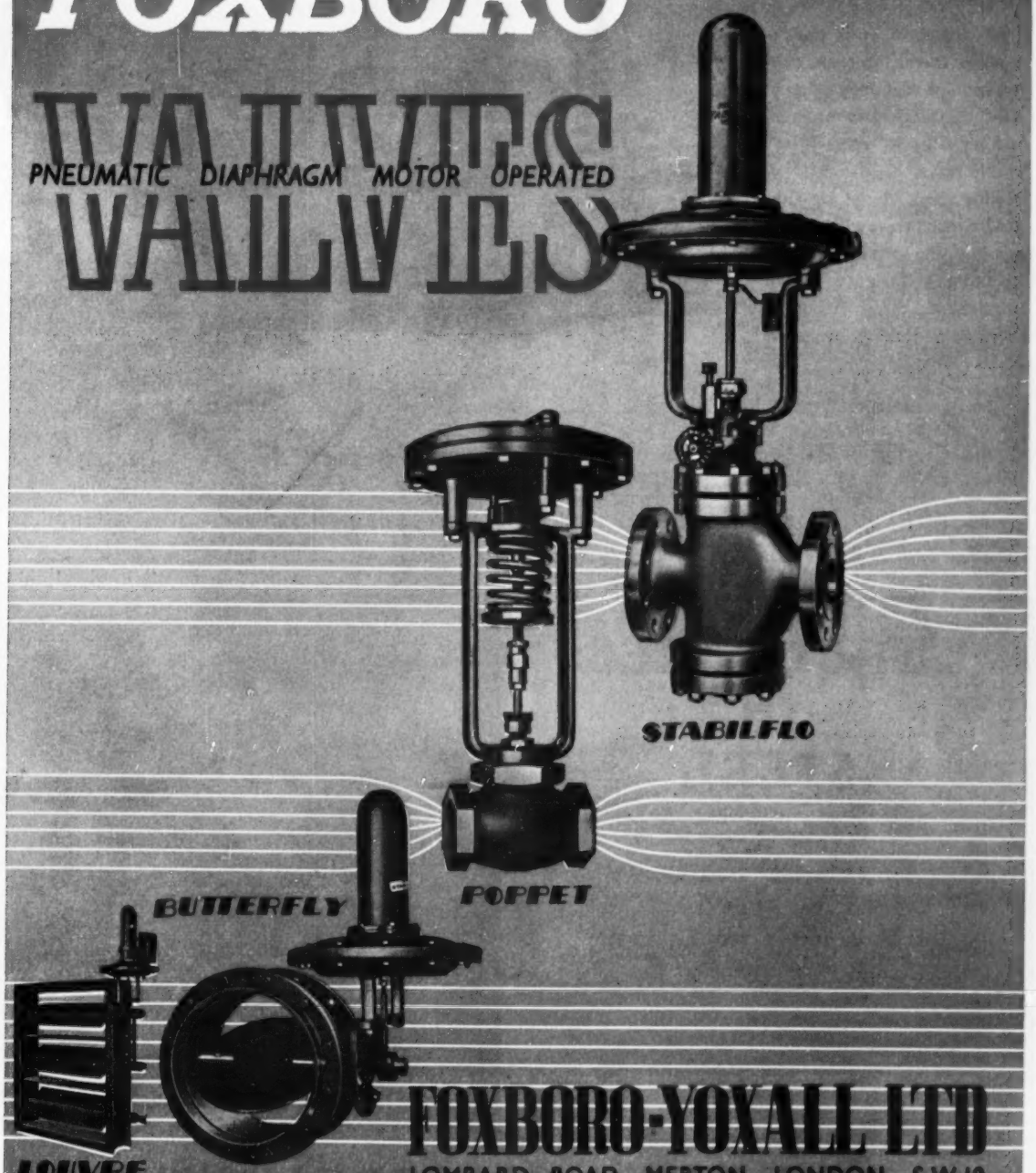

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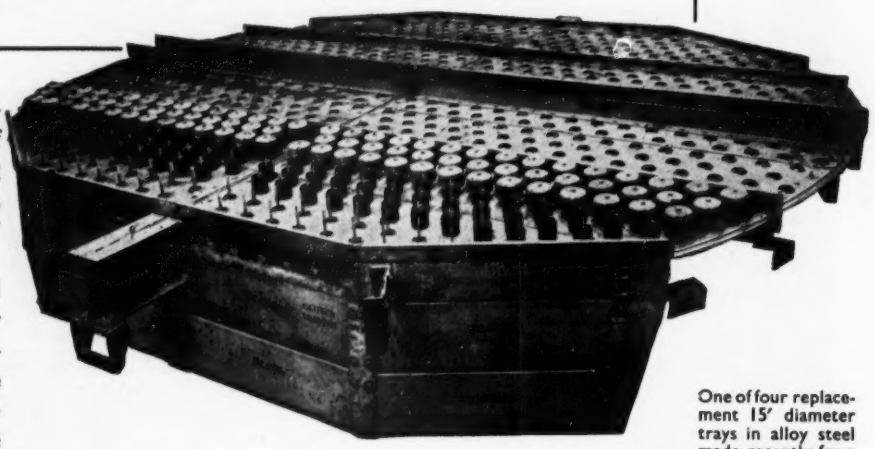

One of four replacement 15′ diameter trays in alloy steel made recently for a Middle East refinery.

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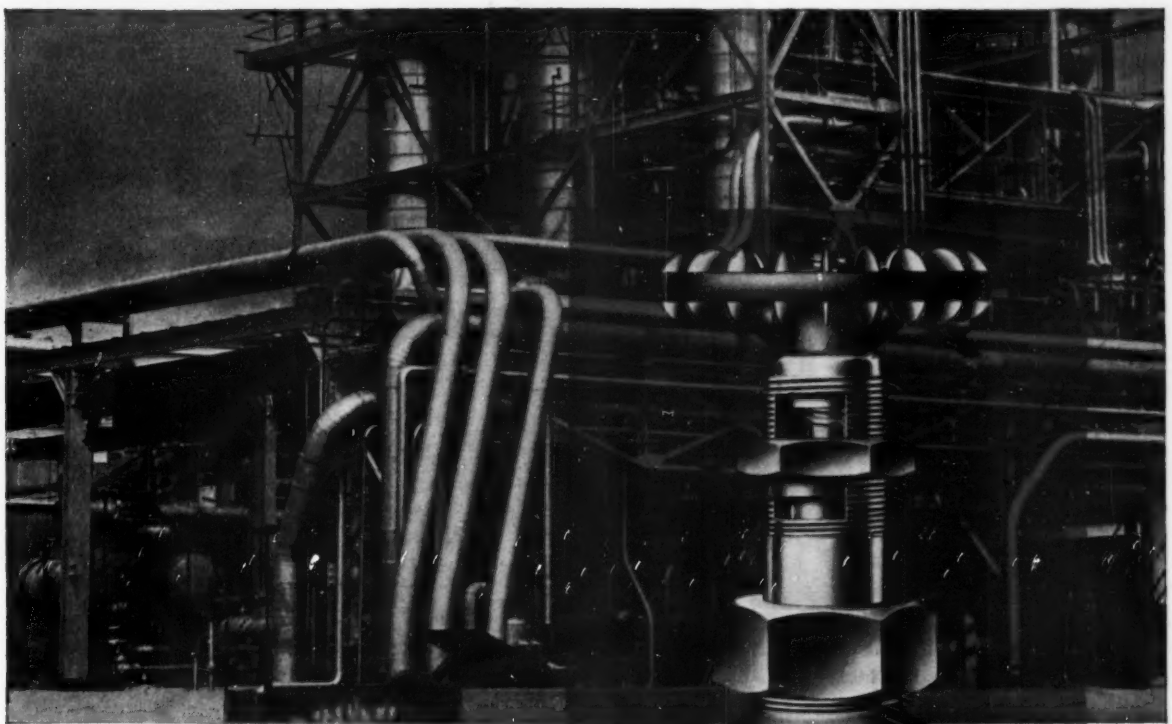
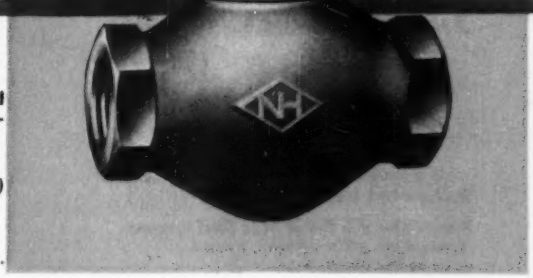


A SHELL PHOTO



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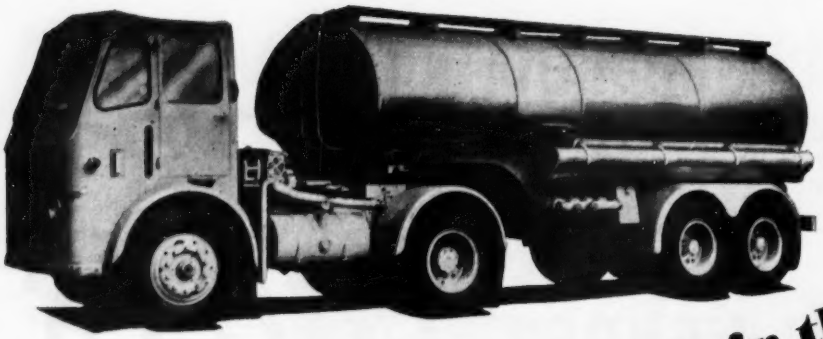

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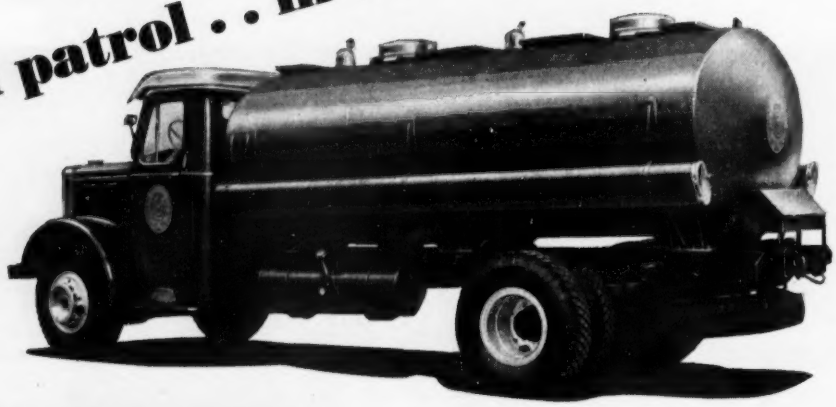

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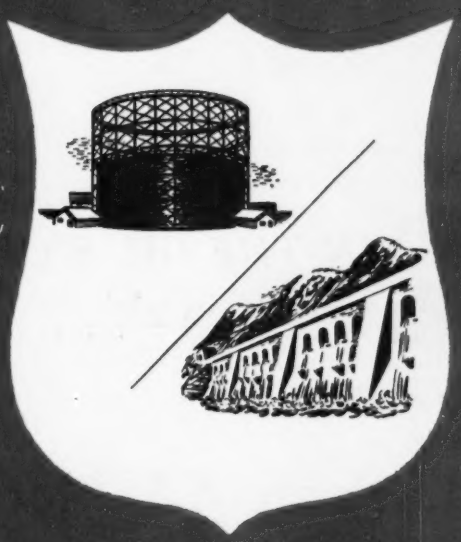

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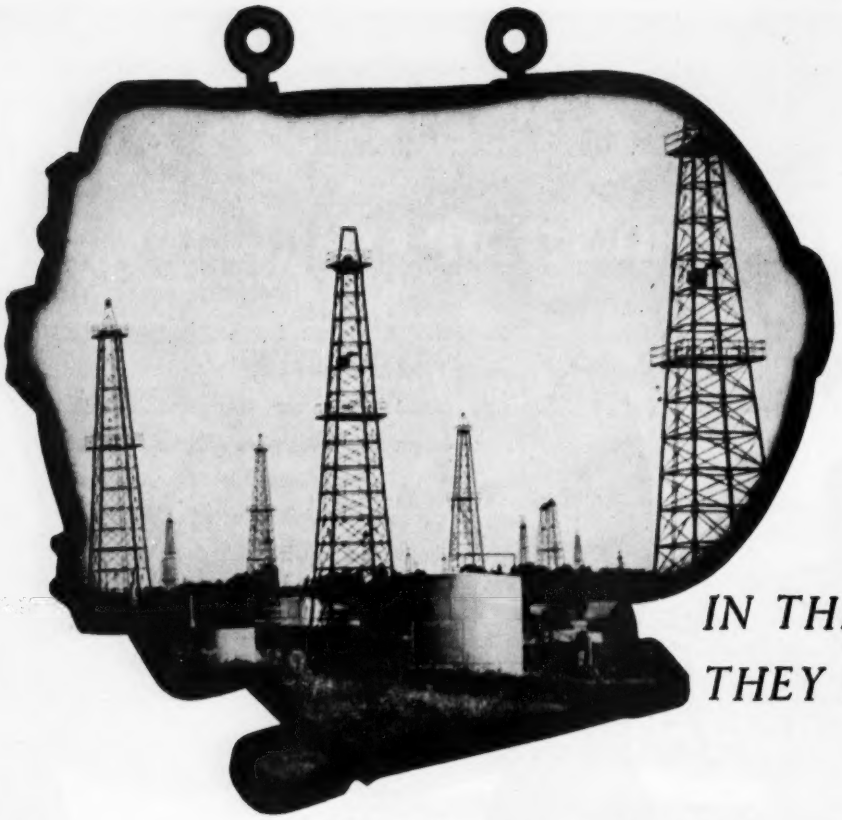

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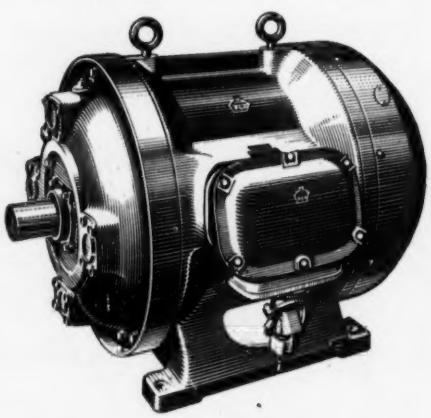

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